RECENT RESULTS FROM MINOS AND FUTURE PROSPECTS

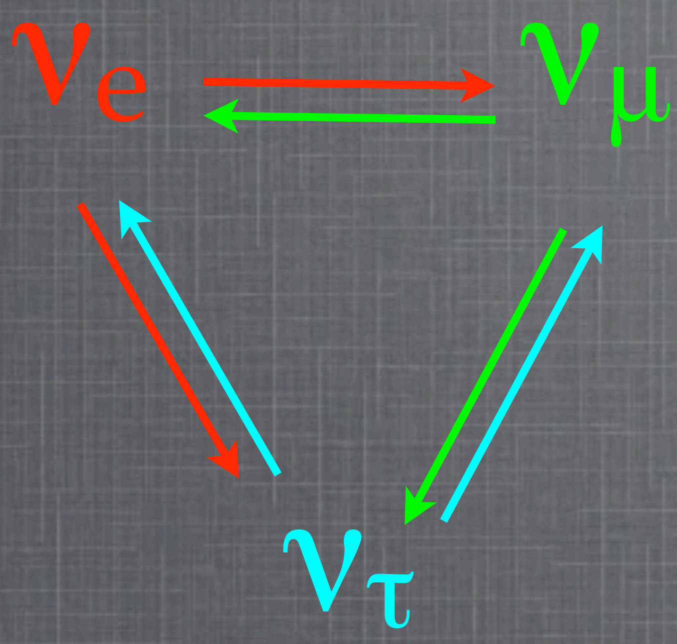
Jonathan M. Paley for the MINOS Collaboration
Indiana University

Fermilab Users' Meeting
June 5, 2008

The MINOS Collaboration

Argonne - Arkansas Tech - Athens - Benedictine - Brookhaven - Caltech - Cambridge - Campinas - Fermilab - Harvard - IIT - Indiana - Minnesota-Twin Cities - Minnesota-Duluth - Oxford - Pittsburgh - Rutherford - São Paulo - South Carolina - Stanford - Sussex - Texam A&M - Texas-Austin - Tufts - UCL - Warsaw - William & Mary

Goals of the MINOS Experiment



- Make precise measurement of Δm^2 and $\sin^2(2\theta)$

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta)\,\sin^2(1.27\,\Delta m^2\,L/E)$$

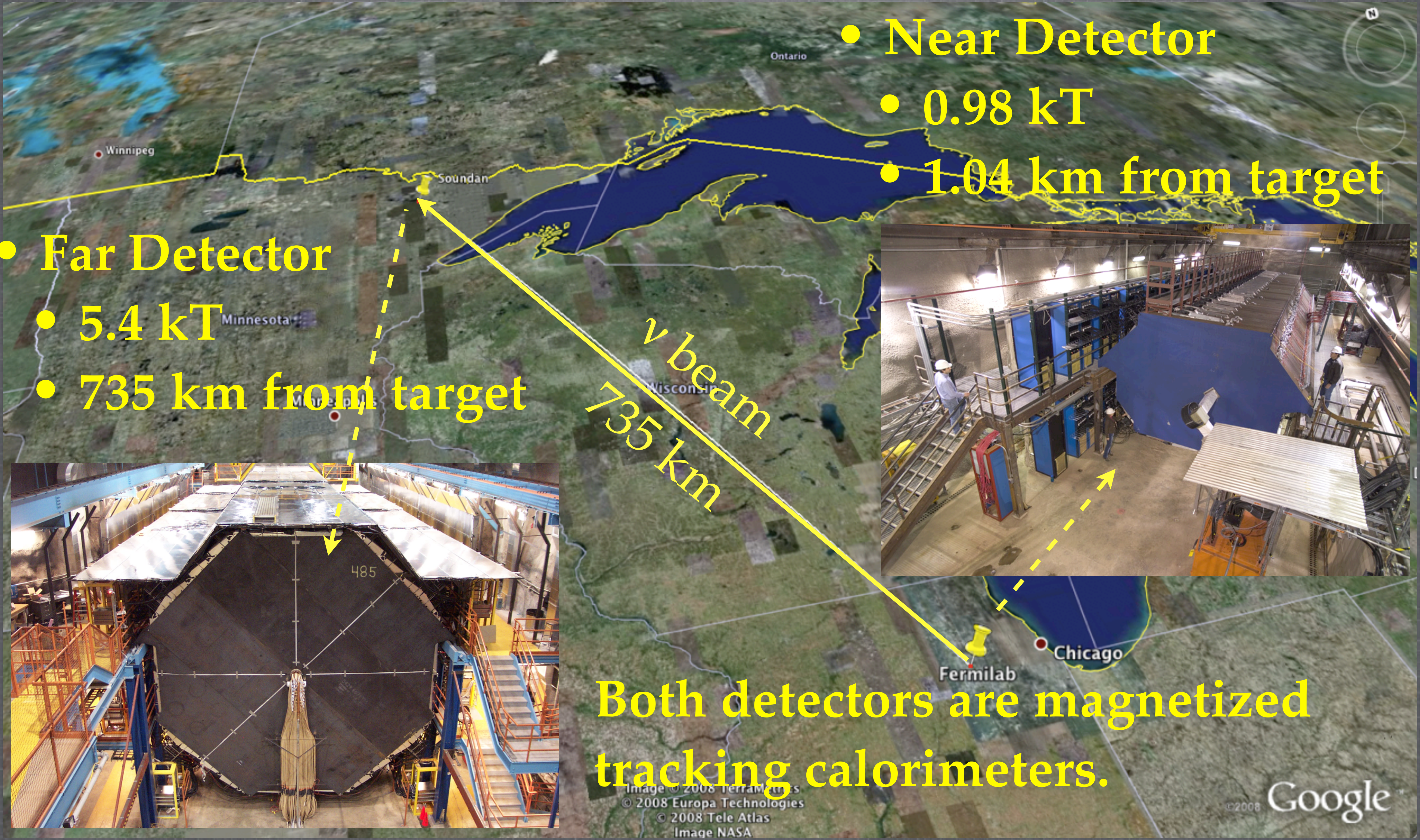
- Confirm oscillations vs. other explanations (decay, decoherence)

- Secondary goals:
  - Search for subdominant $\nu_\mu \rightarrow \nu_e$
  - Search for sterile neutrinos
  - CPT tests
  - Atmospheric neutrino and cosmic ray studies

2007-08: Very Productive Year!

- 2 boxes opened (ν_μ CC and NC blind analyses), PRLs to be submitted soon.
- 8 Ph.D. theses
- Significant progress in understanding backgrounds and systematic uncertainties in all analyses

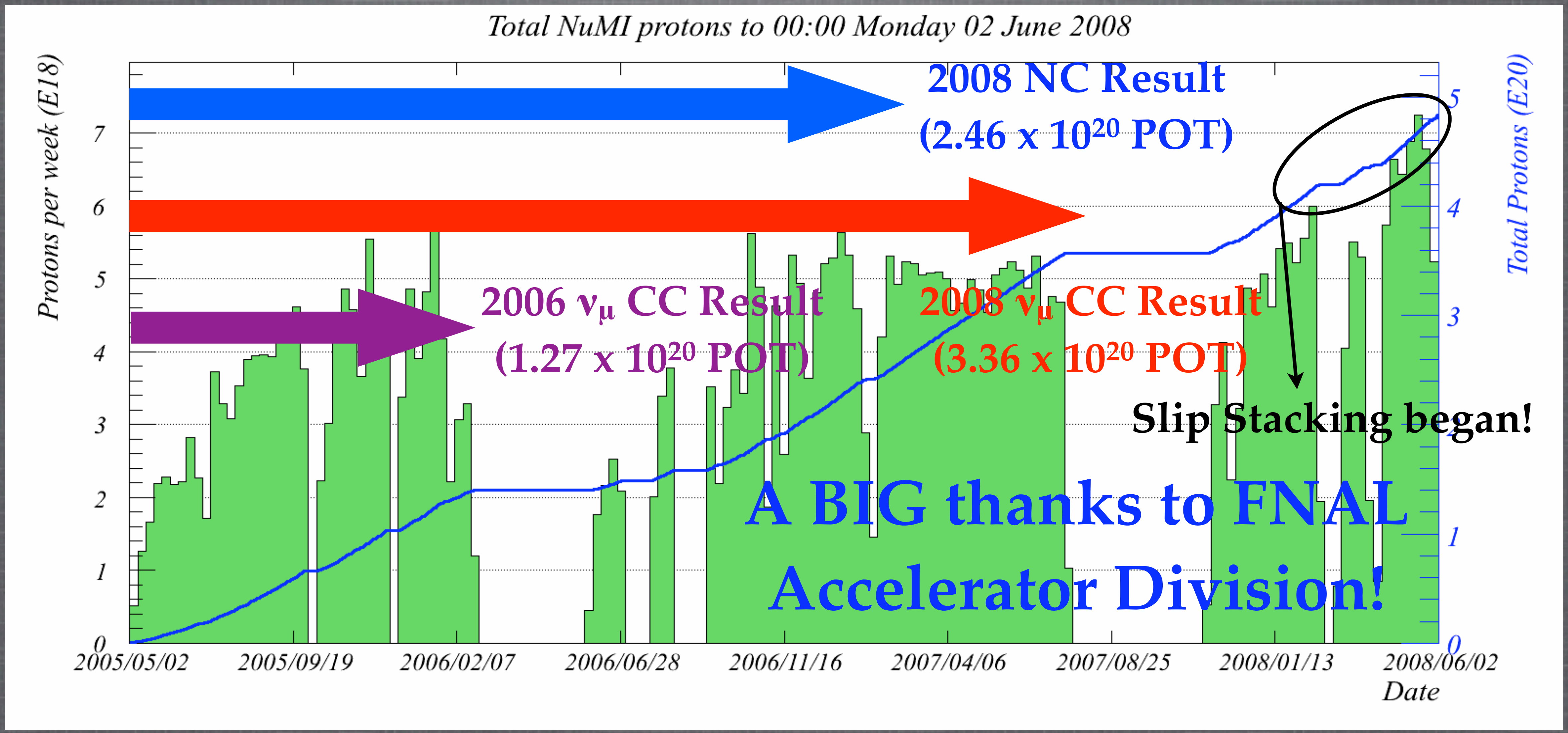
The MINOS Experiment



- Near Detector
  - 0.98 kT
  - 1.04 km from target
- Far Detector
  - 5.4 kT
  - 735 km from target

Both detectors are magnetized tracking calorimeters.

NuMI Beam



Run I
1.27×10^{20} POT

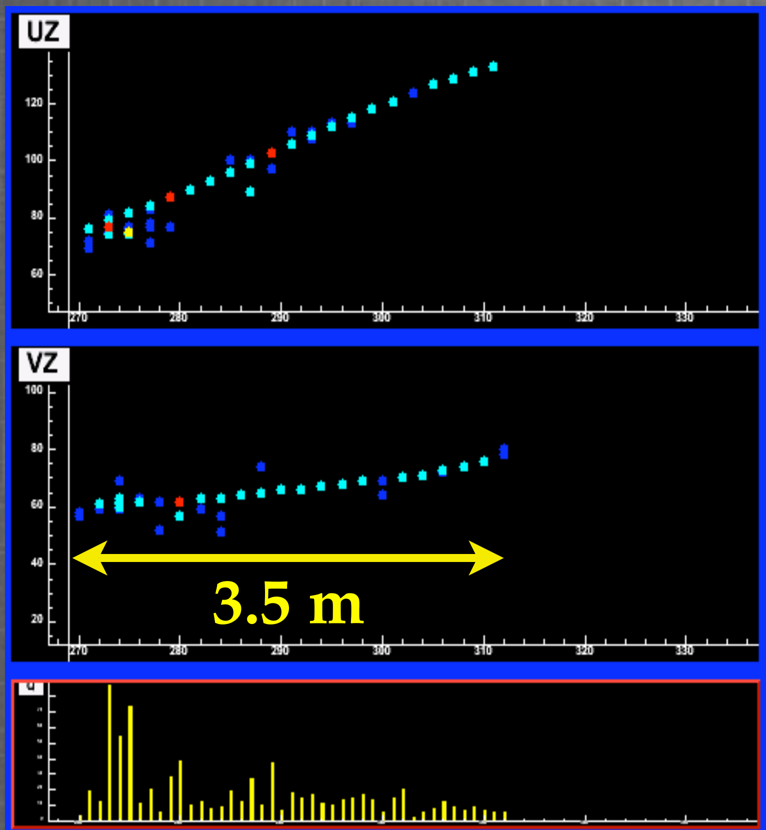
Run II
1.94×10^{20} POT

Run III
1.1×10^{20} POT

Other beam configurations, including HE beam:
0.15×10^{20} POT

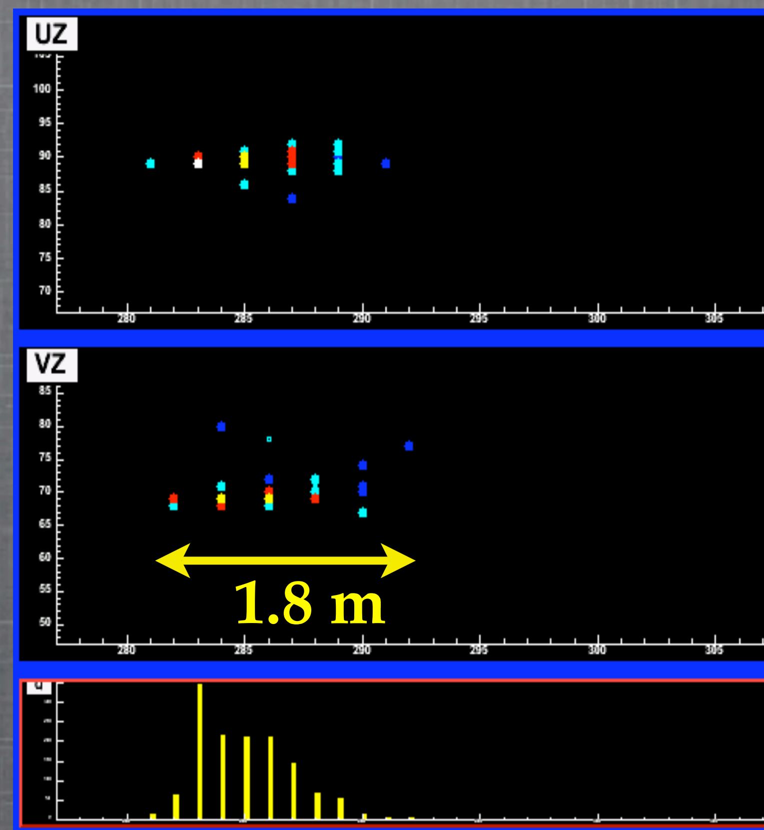
Identifying Events in MINOS

ν_μ CC event



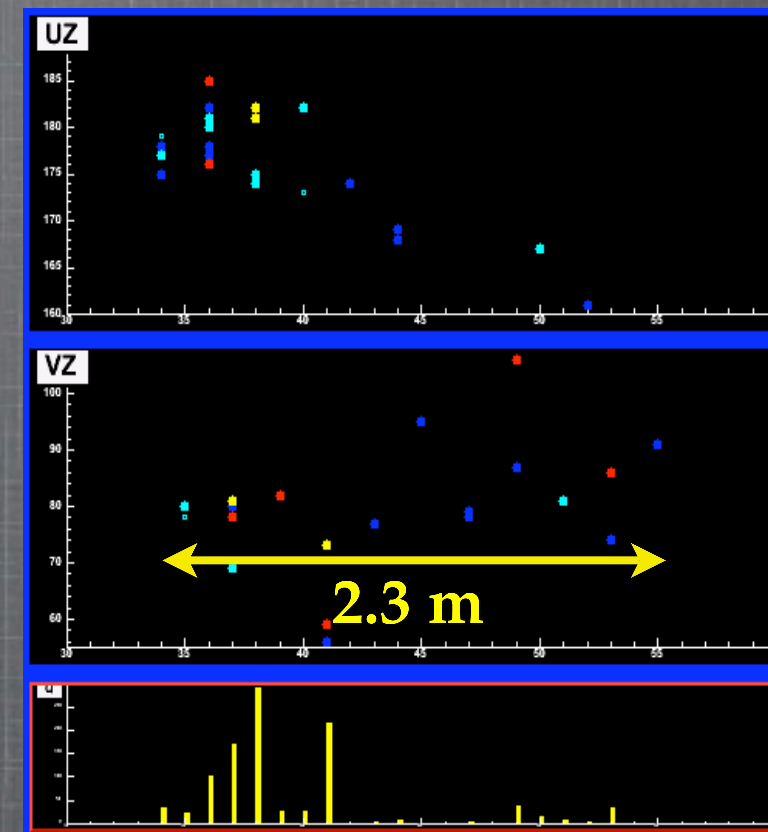
Long μ track +
shower at vertex

ν_e CC event



Short event with
EM shower profile.

NC event

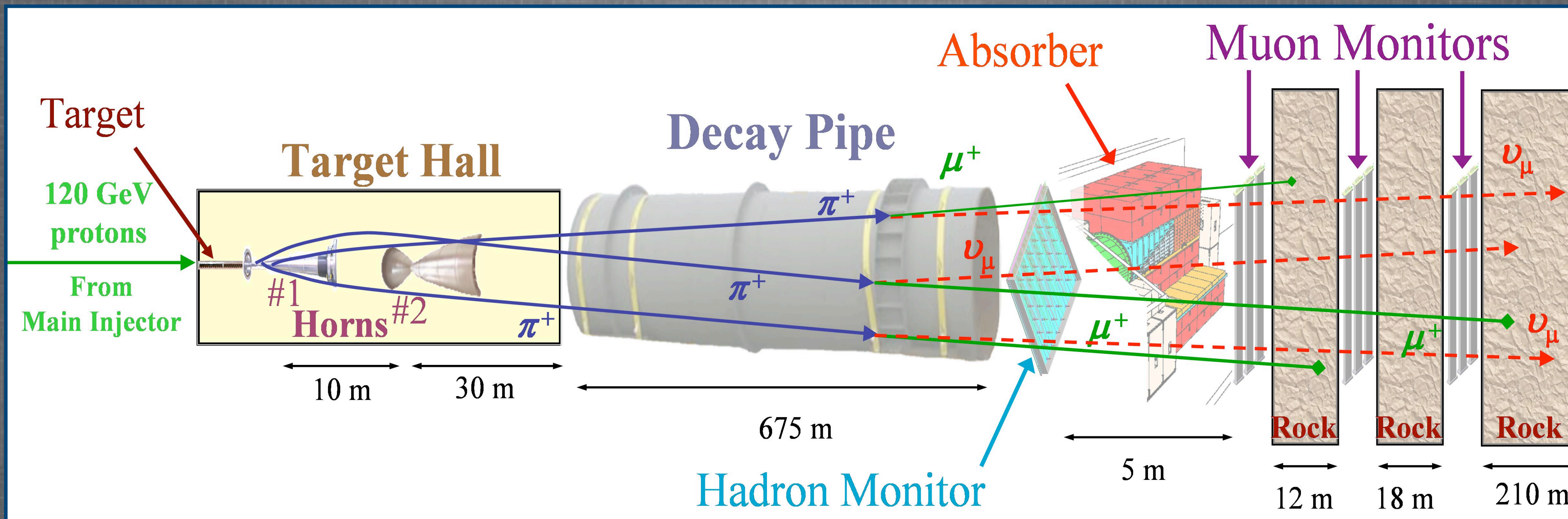


Short, diffuse event.

$$E_\nu = E_{shower} + E_{\mu,e}$$

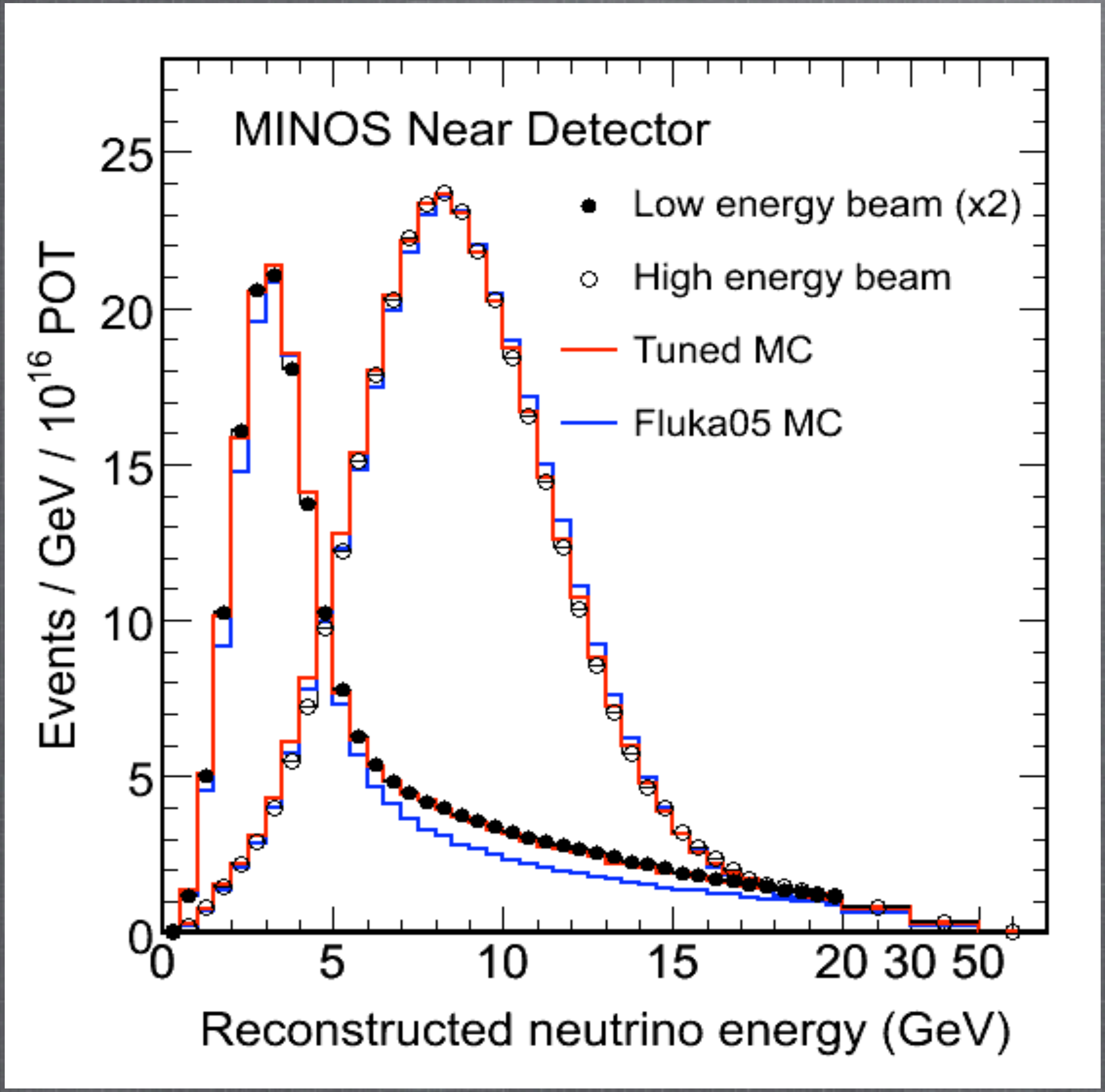
$\delta E_{shower} = 55\%/\sqrt{E}$ $\delta E_\mu = 6\%$ range, 10% curvature

Producing Neutrinos at the Main Injector



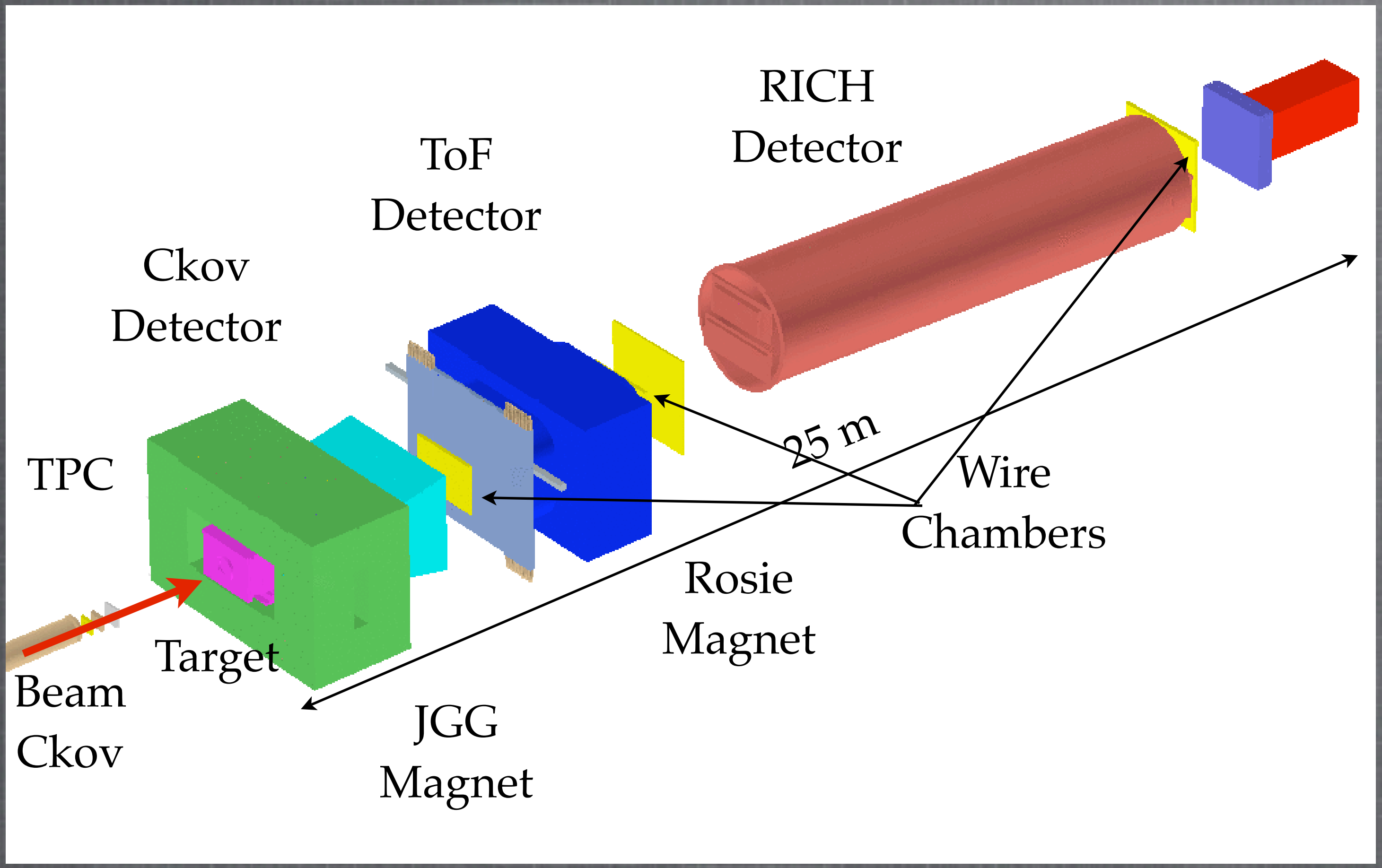
- Neutrinos are produced from secondary mesons created in 120 GeV/c p + graphite target interactions.
- The secondary mesons are focused by two magnetic horns; ν beam energy is *tunable* by moving target position longitudinally w.r.t. the horn positions.
- In LE beam configuration, beam is composed of 92.9% ν_μ, 5.8% $\bar{\nu}_\mu$, and 1.3% ν_e and $\bar{\nu}_e$.

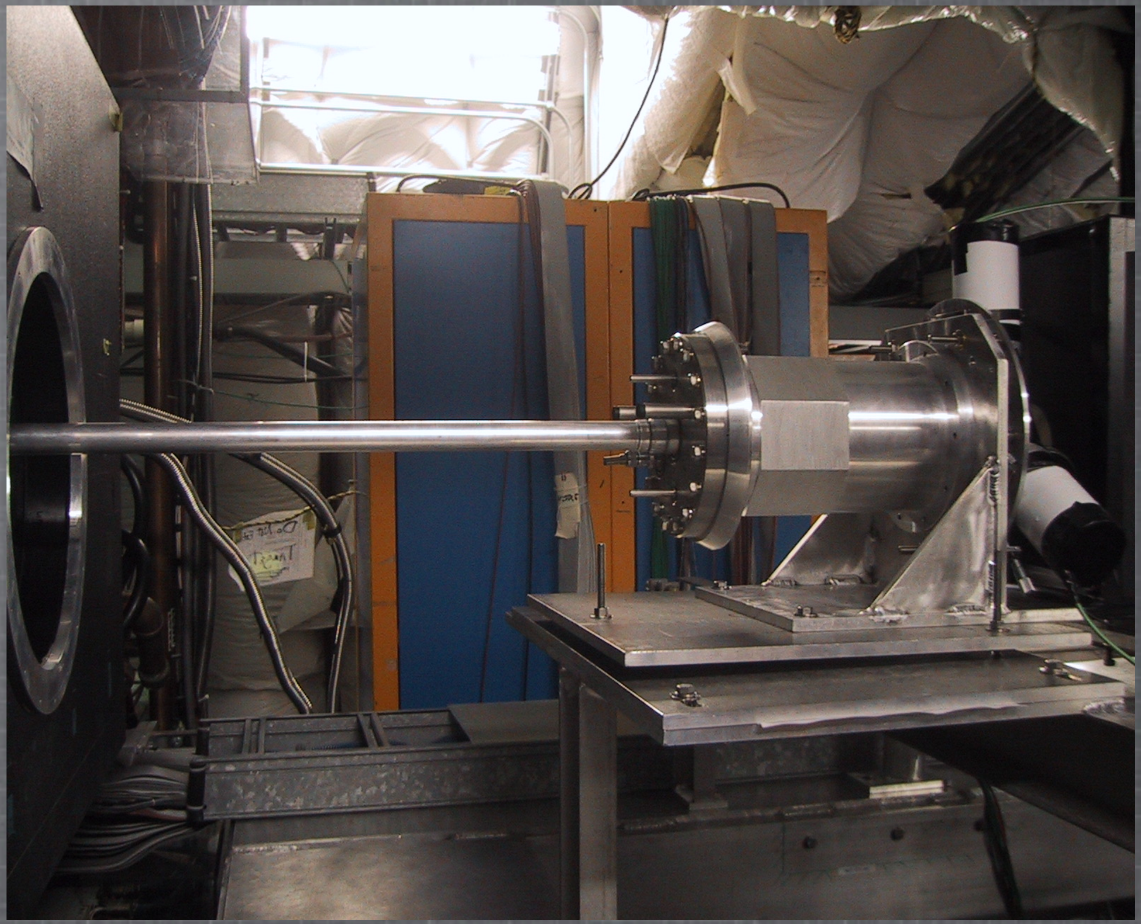
Predicting the Flux



- MINOS uses Fluka06 MC to predict the ν flux.
- Uncertainty on flux is ~30% due to lack of hadron production data.
- To improve our data-to-MC agreement, we tune the Fluka MC to ND energy spectra of different beam configurations.
- These beam-reweighted spectra are used in all analyses discussed today.

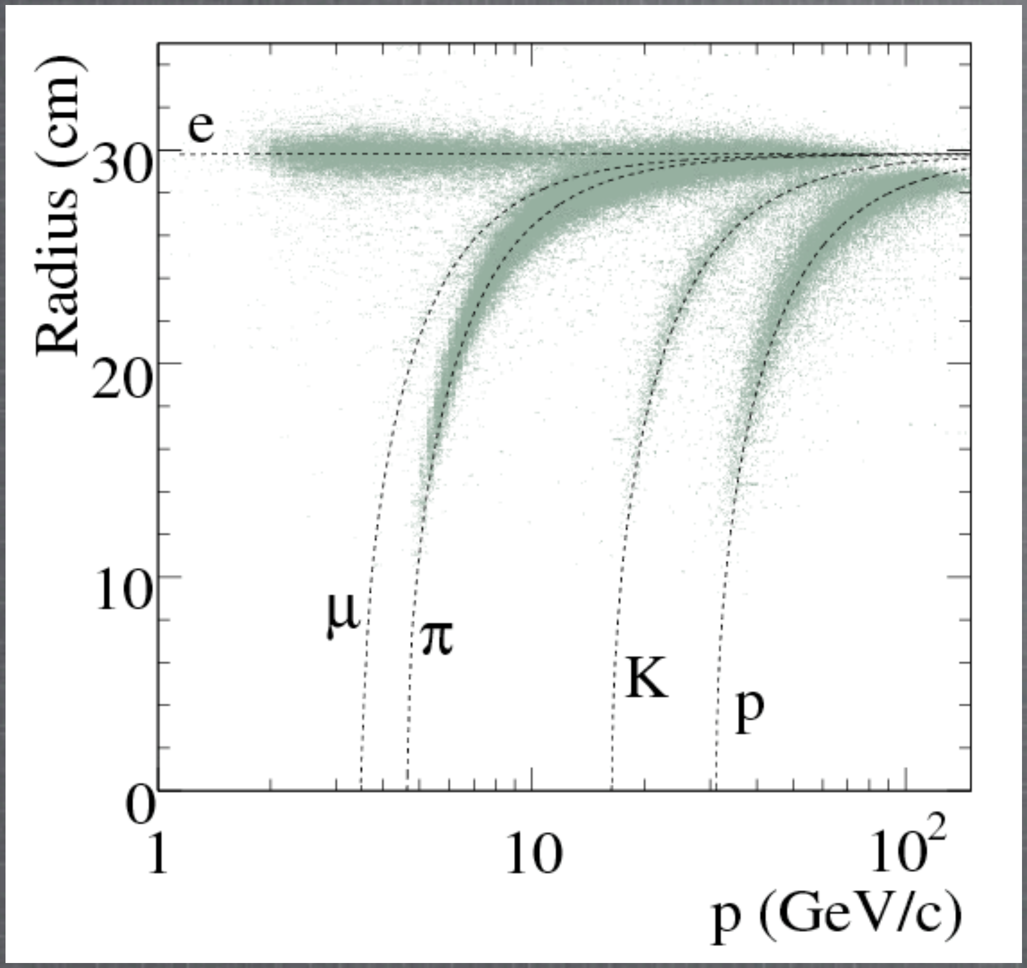
Measurement of Hadron Production off NuMI Target in MIPP

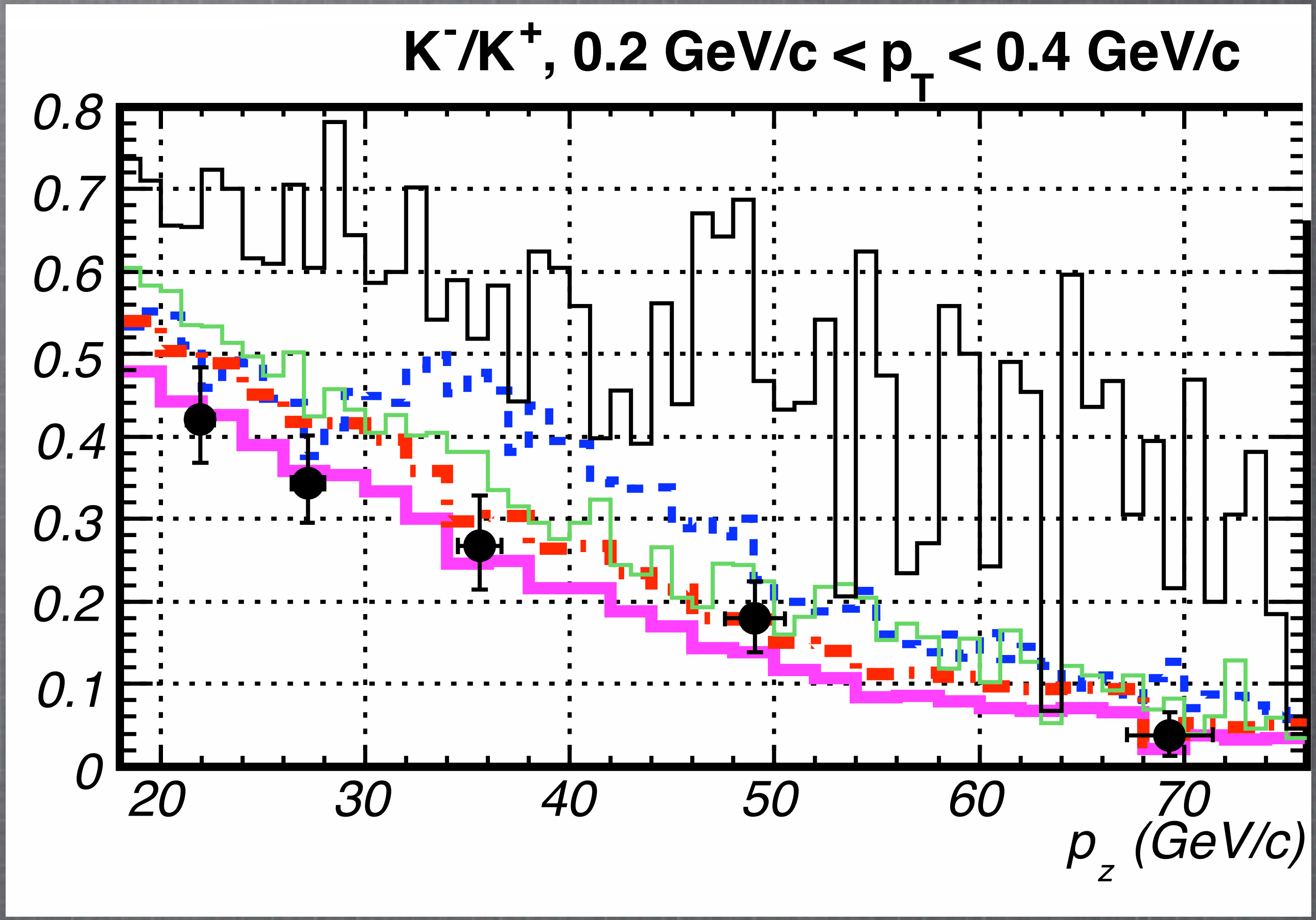




- Main Injector Particle Production (MIPP) is a fixed target experiment with beams of π, K and p from 5-120 GeV/c and LH2, C, Be, Bi, U targets.
- MIPP has collected 1.6 x 10^6 events of 120 GeV p striking the MINOS target.

Status of MIPP Analysis



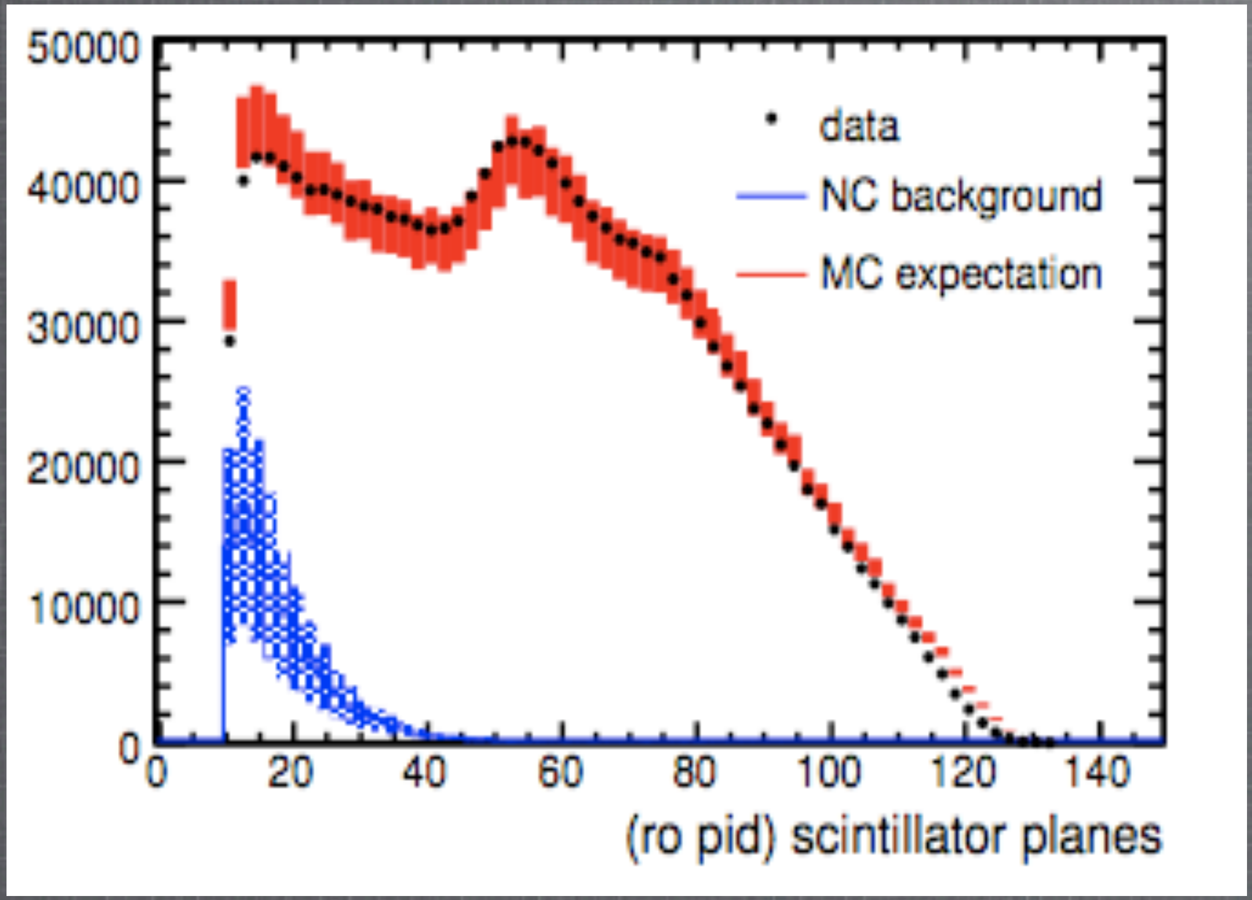


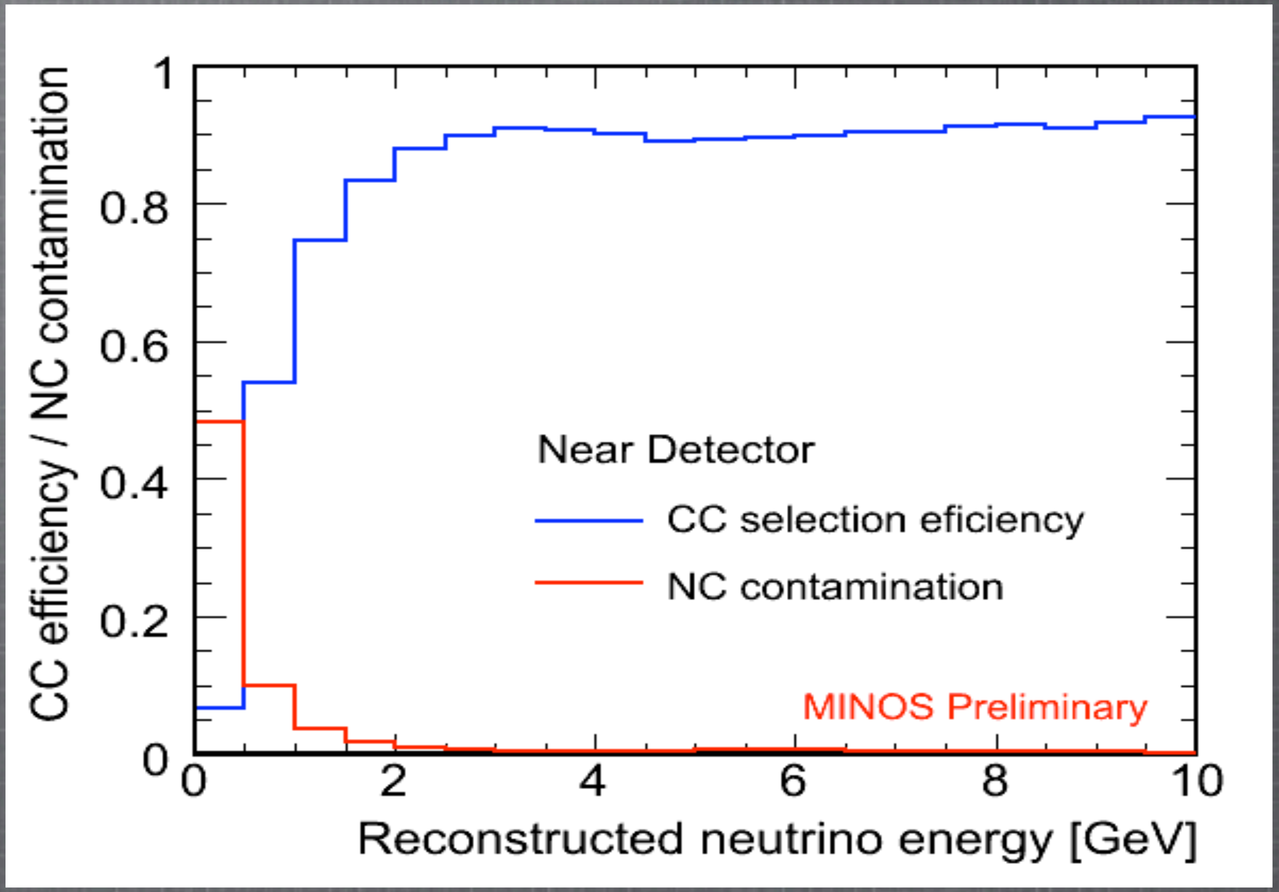
- π^-/π^+, K^-/K^+ , and K/π production ratios above 20 GeV/c agree well with expectations from MINOS beam-tuning.
- The MIPP Collaboration has completed the calibration of all PID detectors and is now focusing on the hadron production measurement from the NuMI target data set. Expected flux uncertainty is ~15% (statistics-limited).
- The proposed MIPP upgrade would allow a systematics-limited measurement of the NuMI flux to within a few percent.
- See poster by Yusuf Gunaydin.

ν_μ CC Analysis

Precision measurement of Δm^2 and $\sin^2(2\theta)$

ν_μ CC Event Selection

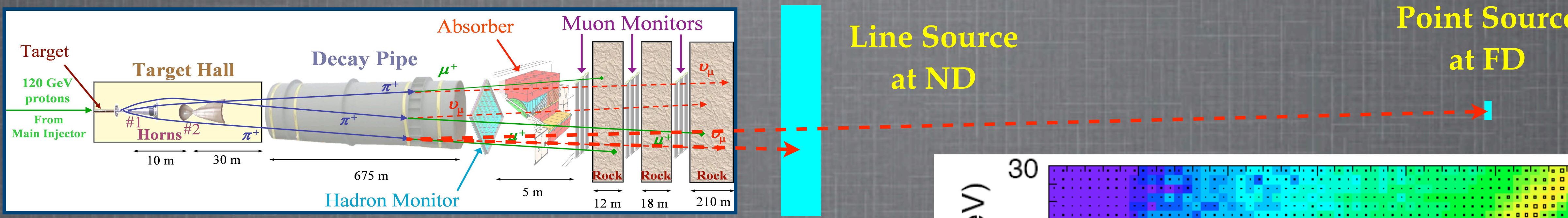


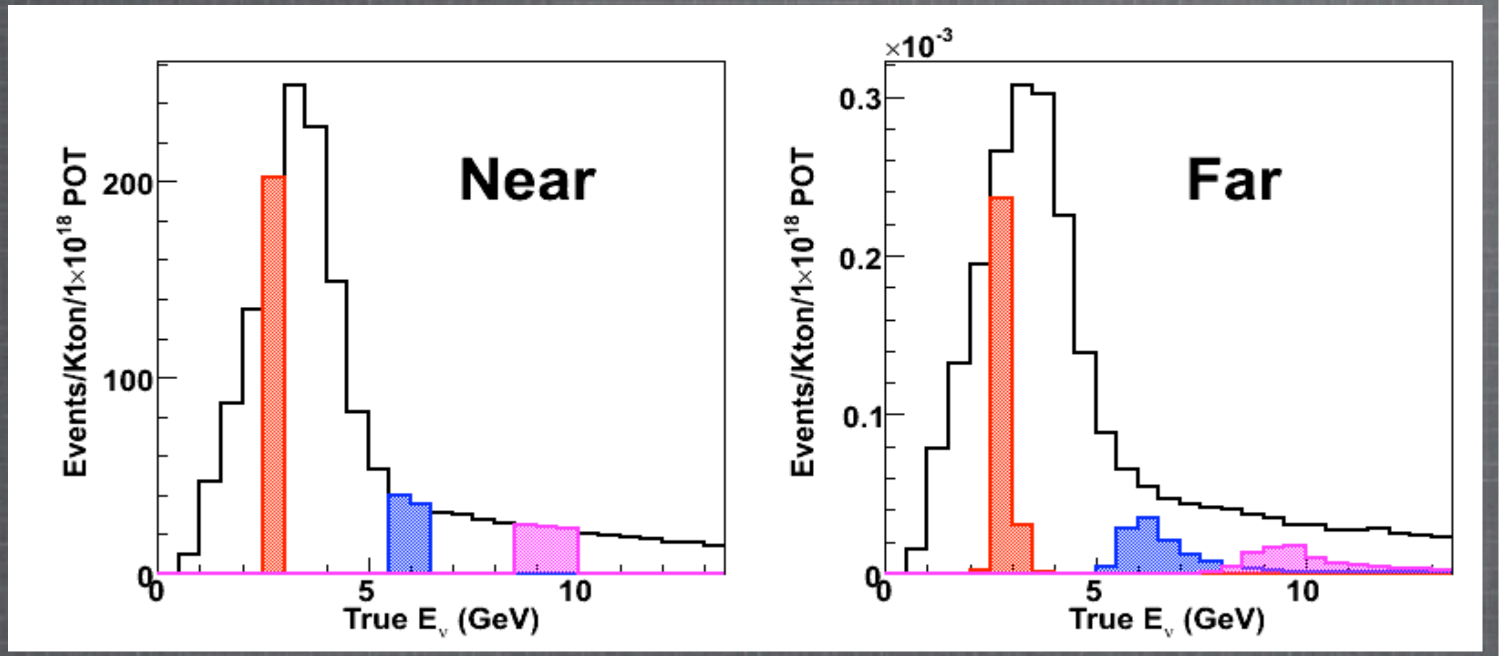


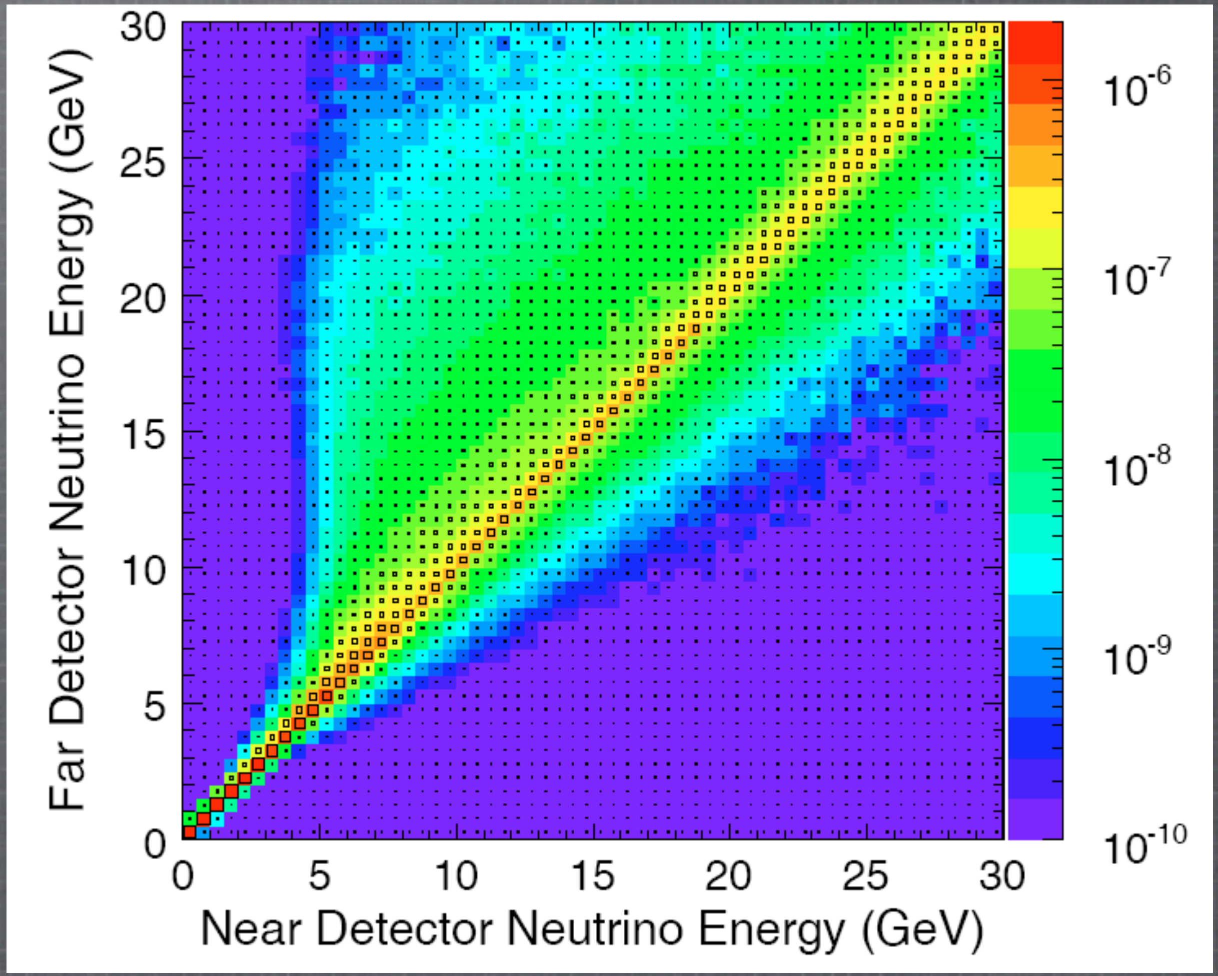
- CC/NC separation achieved via a kNN event selection based on:
  - Track length
  - Mean pulse height
  - Fluctuation in pulse height
  - Transverse track profile

- Cut on separation parameter maximizes CC selection efficiency and minimizes NC background.
- Good agreement between data and MC above the CC/NC separation parameter cut.

Expected Far Detector Spectrum

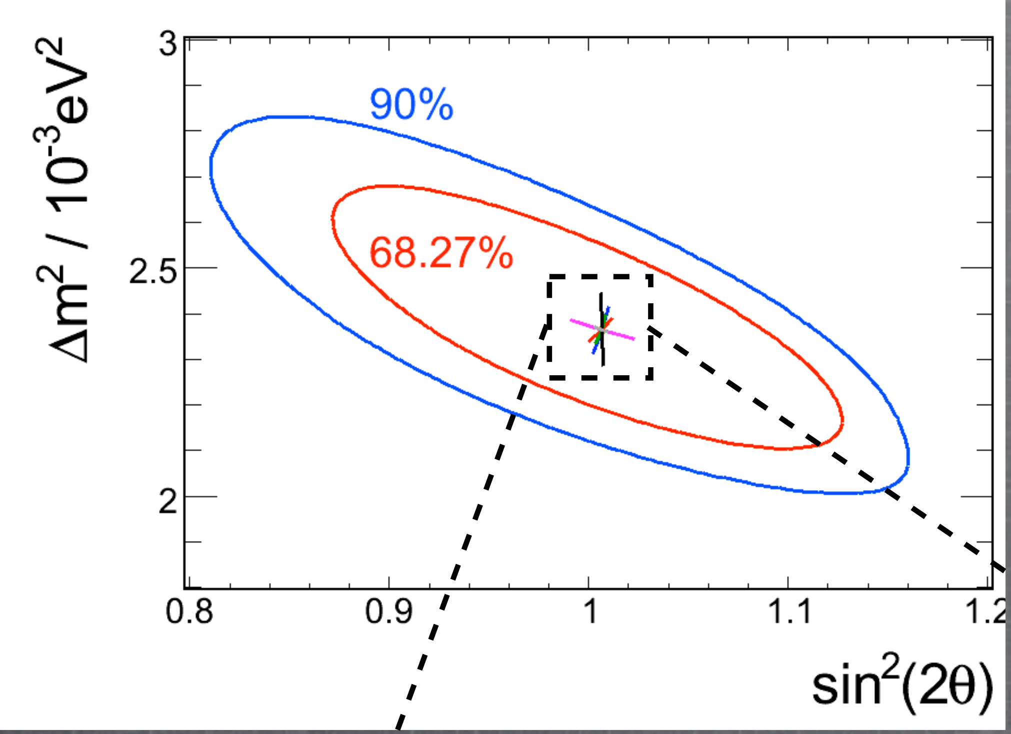




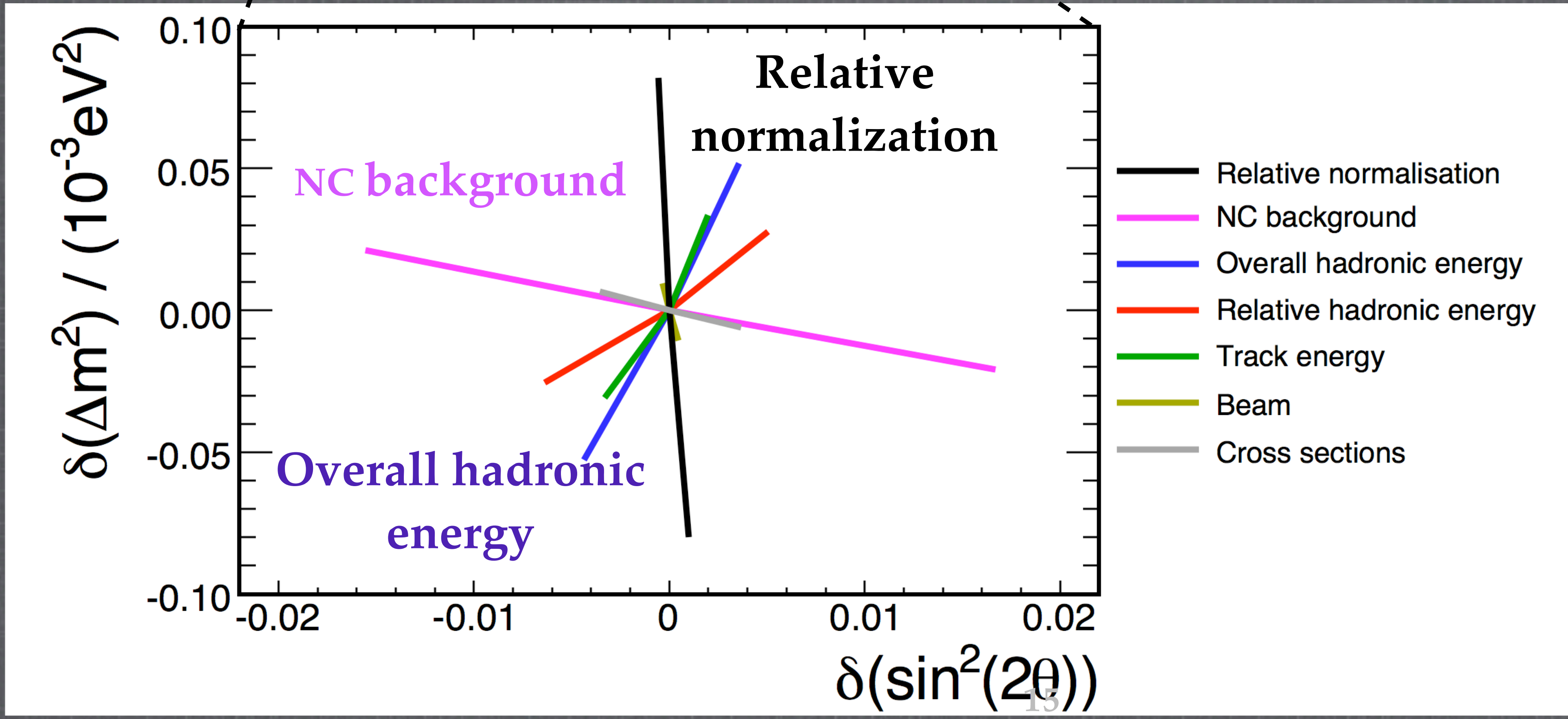


- Near detector spectrum is extrapolated to the far detector.
- Use MC to provide energy smearing and acceptance corrections.

Systematic Uncertainties

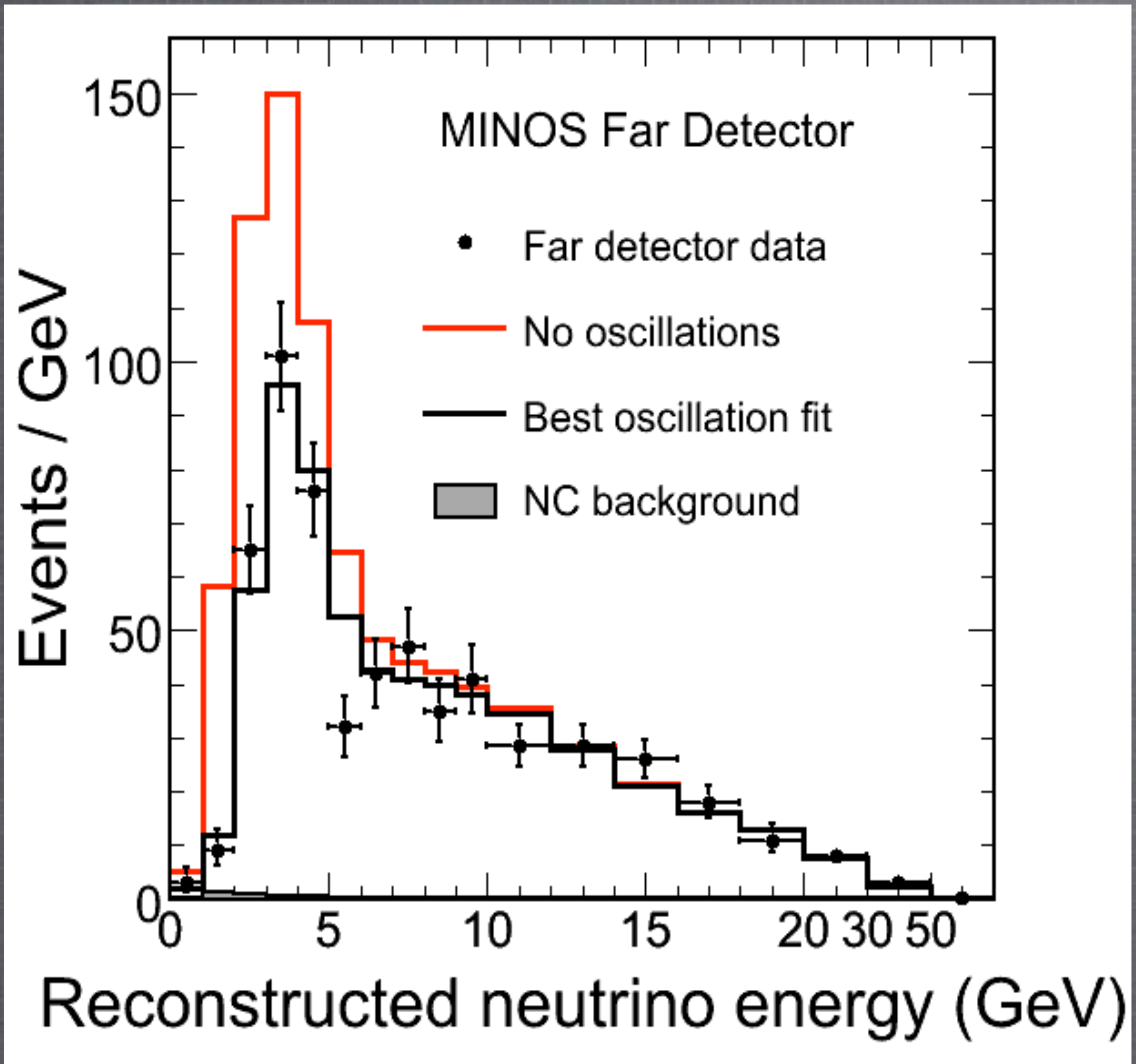


- Systematic uncertainties estimated by fitting modified MC in place of data.
- ν_μ CC measurement is statistics limited.
- Dominant uncertainties are:
  - ND/FD relative normalization (Δm^2)
  - Overall hadronic energy calibration (Δm^2)
  - NC background ($\sin^2(2\theta)$)



- These three systematic effects are included in the final fit as nuisance parameters.

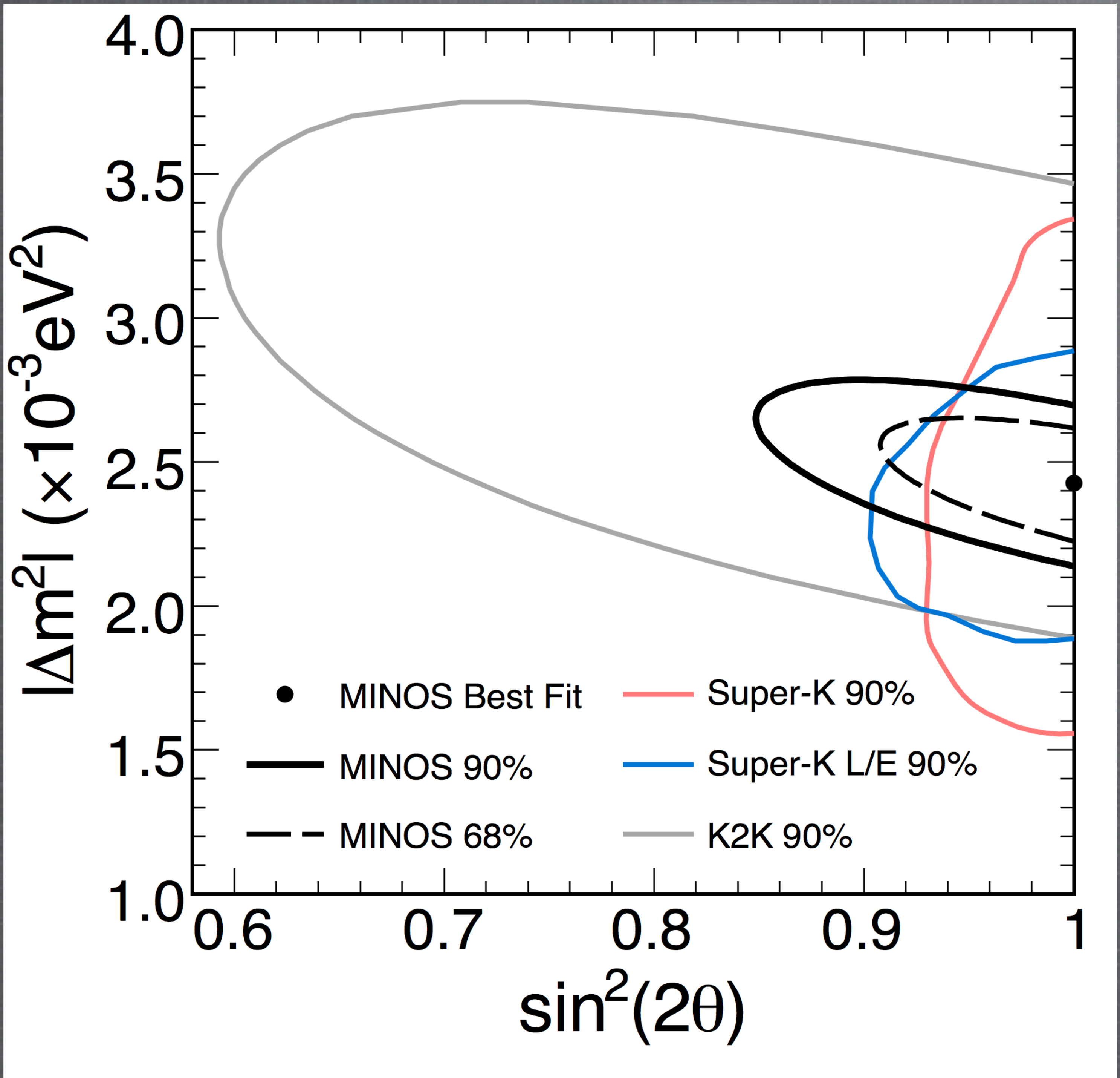
FD Energy Spectrum/Performing the Fit



- FD energy spectrum is only looked at after performing:
  - low-level data quality checks
  - procedural checks
- 848 events observed in the FD
- 1065 ± 60 expected with no oscillations
- We fit the energy distribution to the oscillation hypothesis:

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta)\,\sin^2(1.27\,\Delta m^2\, L/E)$$

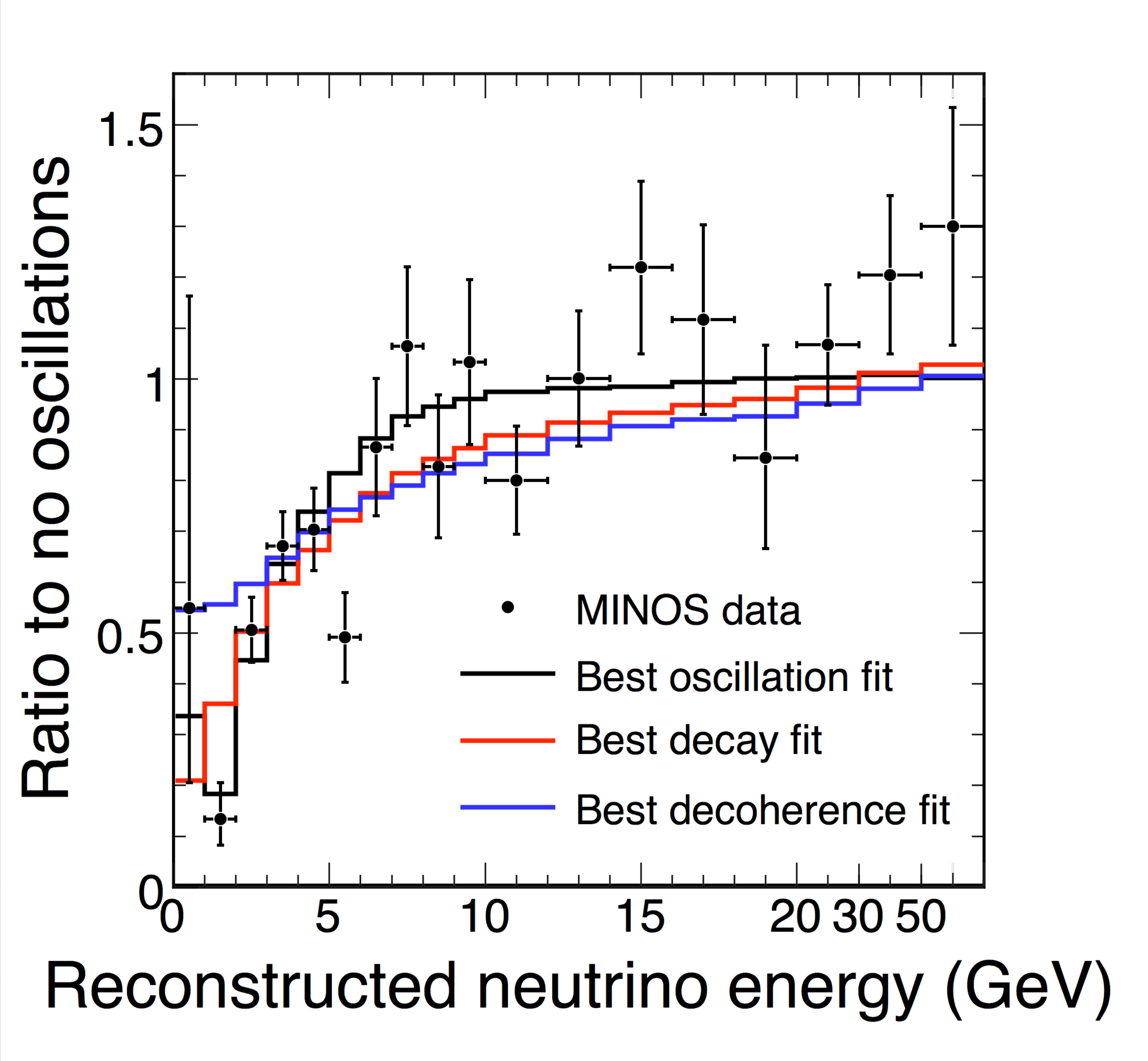
Contours



- **Constrained fit:**
  - $\Delta m^2 = (2.43 \pm 0.13) \times 10^{-3}$ eV^2 (68% CL)
  - $\sin^2(2\theta) > 0.90$ (90% CL)
  - χ^2/ndof = 90/97

- **Unconstrained fit:**
  - $\Delta m^2 = 2.33 \times 10^{-3}$ eV^2
  - $\sin^2(2\theta) = 1.07$
  - $\Delta\chi^2 = -0.6$

Alternative Hypotheses



Decay:

$P_{\mu\mu} = (\sin^2\theta + \cos^2\theta \exp(-\alpha L/E))^2$

V. Barget *et. al.*, PRL82:2640 (1999)

χ^2/ndof = 104/97

$\Delta\chi^2 = 14$

Disfavored at 3.7 σ

Decoherence:

$P_{\mu\mu} = 1 - ½ \sin^2(2\theta)\ (1 - \exp(-\mu^2 L/2E))$

G.L. Fogli, *et. al.*, PRD67:093006 (2003)

χ^2/ndof = 123/97

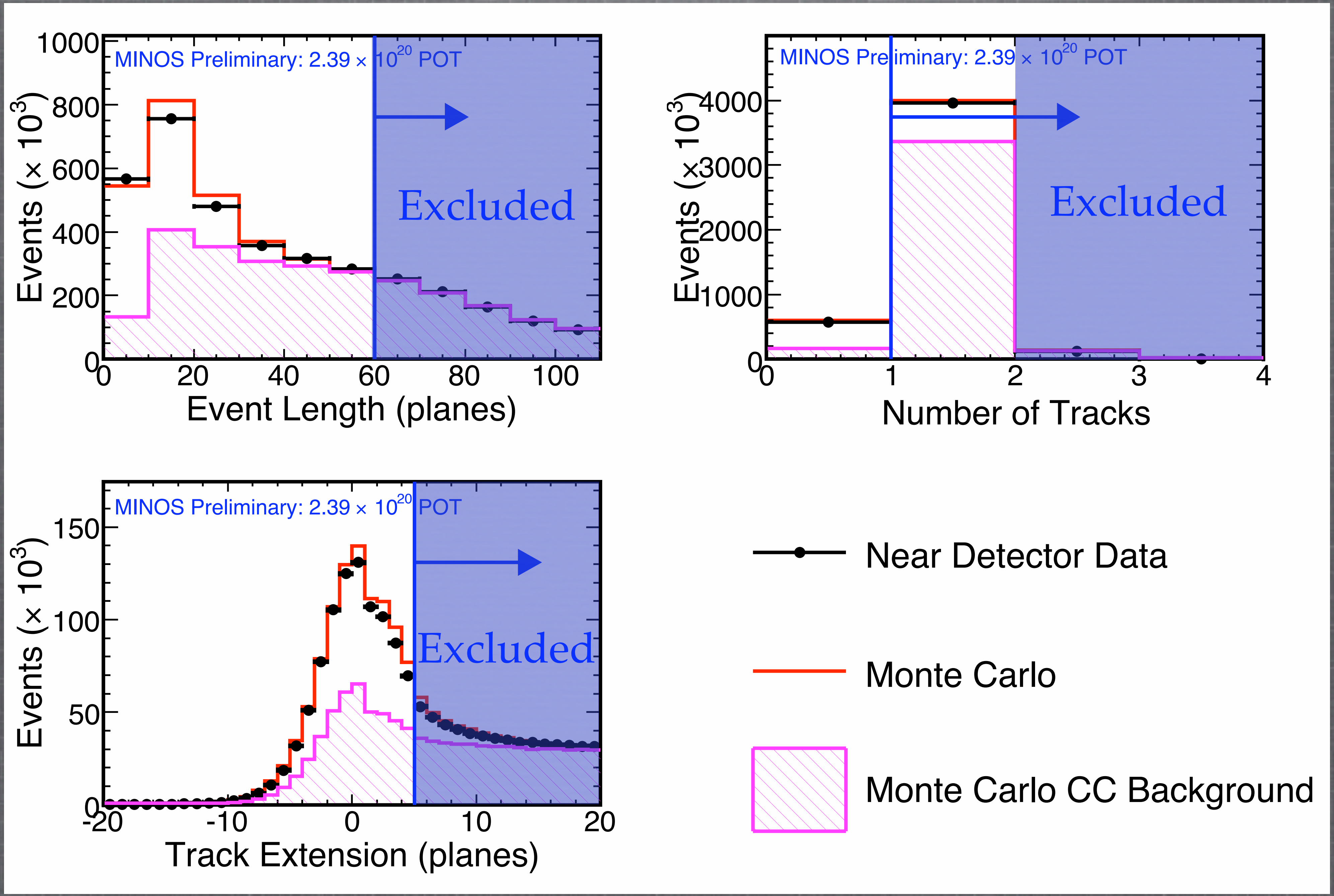
$\Delta\chi^2 = 33$

Disfavored at 5.7 σ

NC Analysis

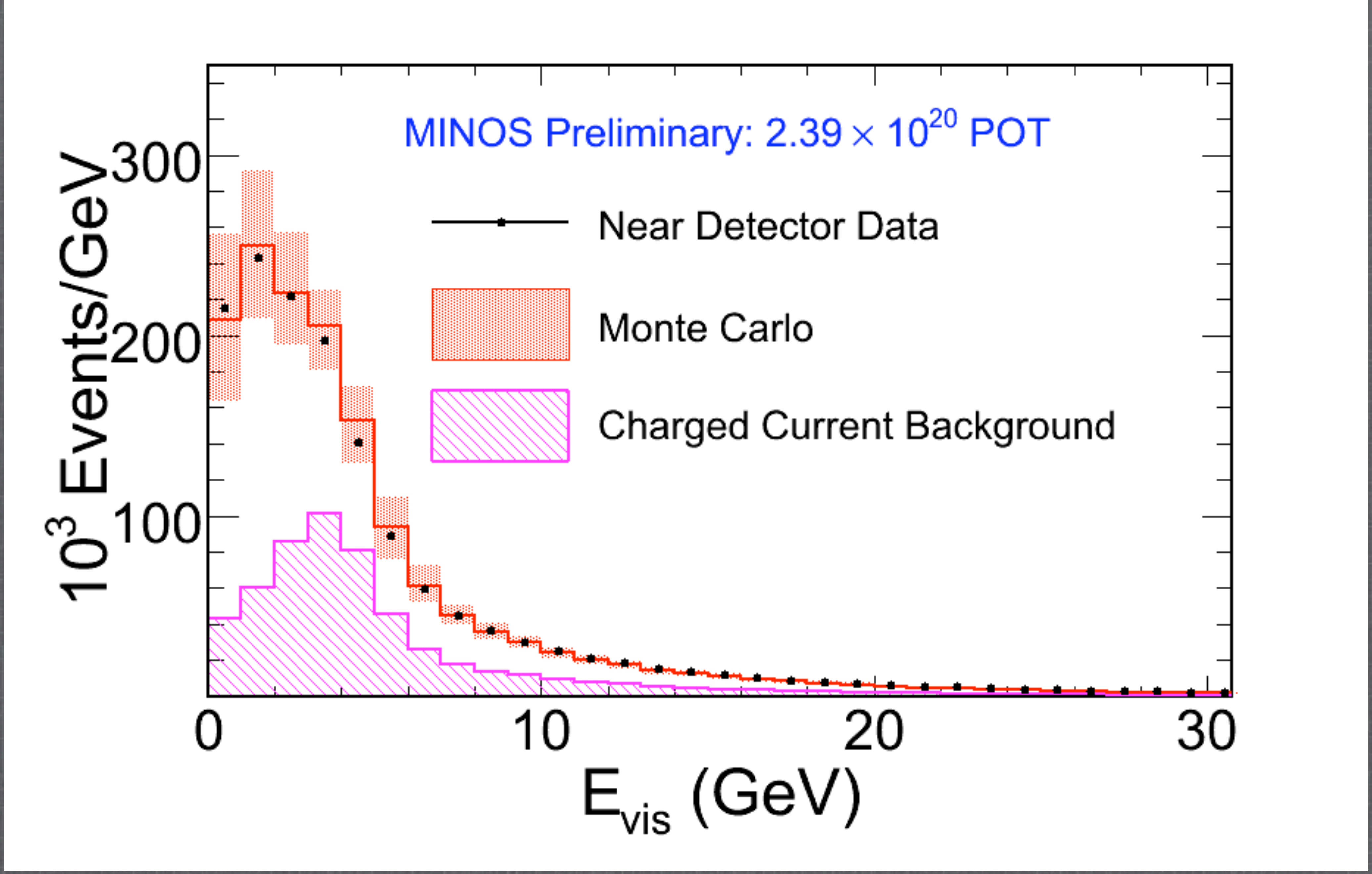
The search for sterile neutrinos

NC Event Selection in the ND



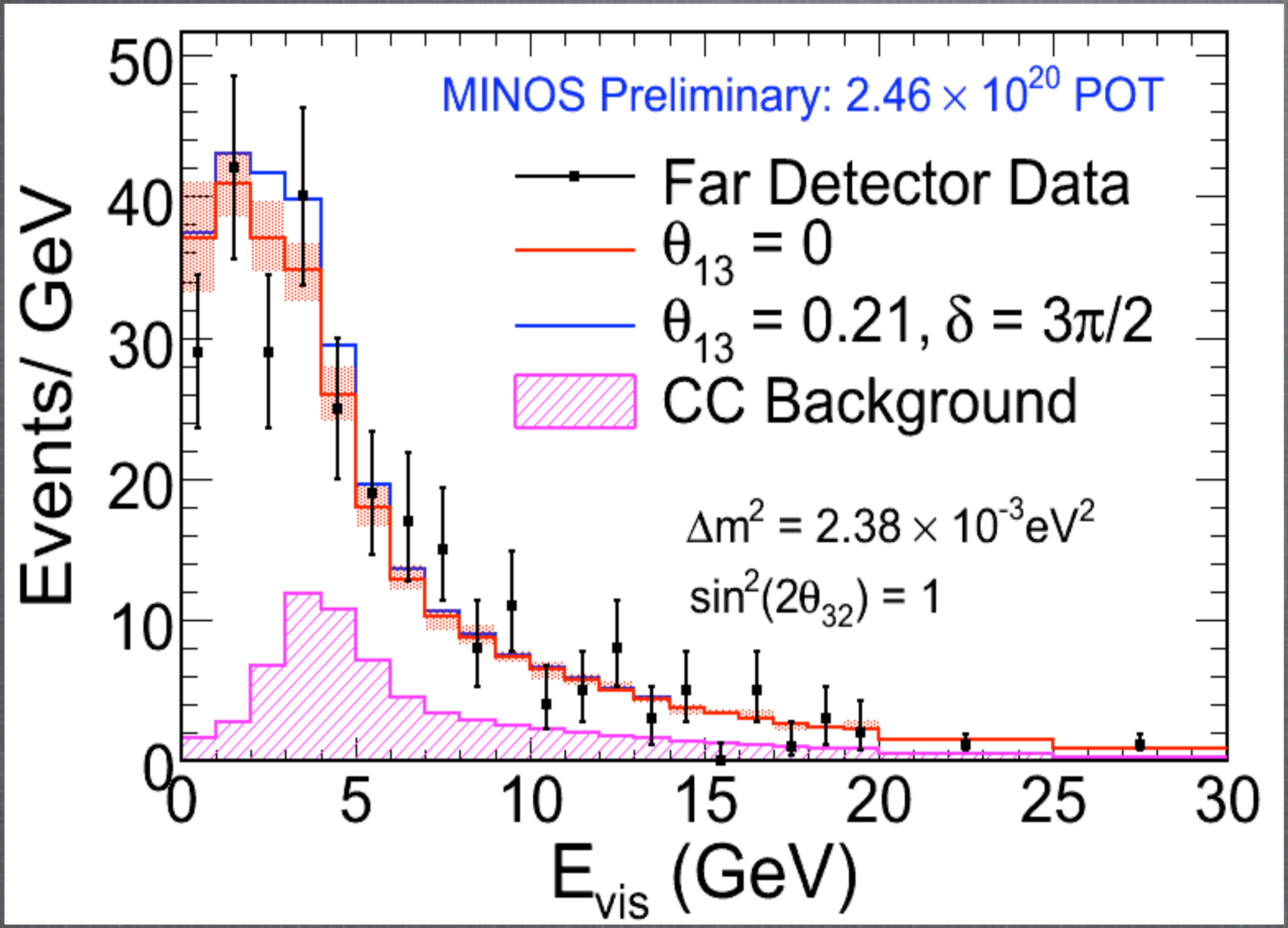
- Since NC events probe active flavors, a depletion of NC events in the FD can only be explained by ν_s.
- We select reconstructed "shower-like" (short) events that fall within a fiducial volume.

Measured Near Detector Spectrum



NC event selection efficiency is 90%, purity is 60%.

3-Flavor Analysis Results



Data/MC Comparison for $\theta_{13} = 0$

Energy Range (GeV)	0 - 3	0 - 120
Data	100	291
MC	115.16 ± 7.67	292.63 ± 15.02
Significance (σ)	1.15	0.10

- **For $E_{vis} < 3$ GeV, $f_{NC} < 35\%$ at 90% CL.**
- **For $E_{vis} < 120$ GeV, $f_{NC} < 17\%$ at 90% CL.**

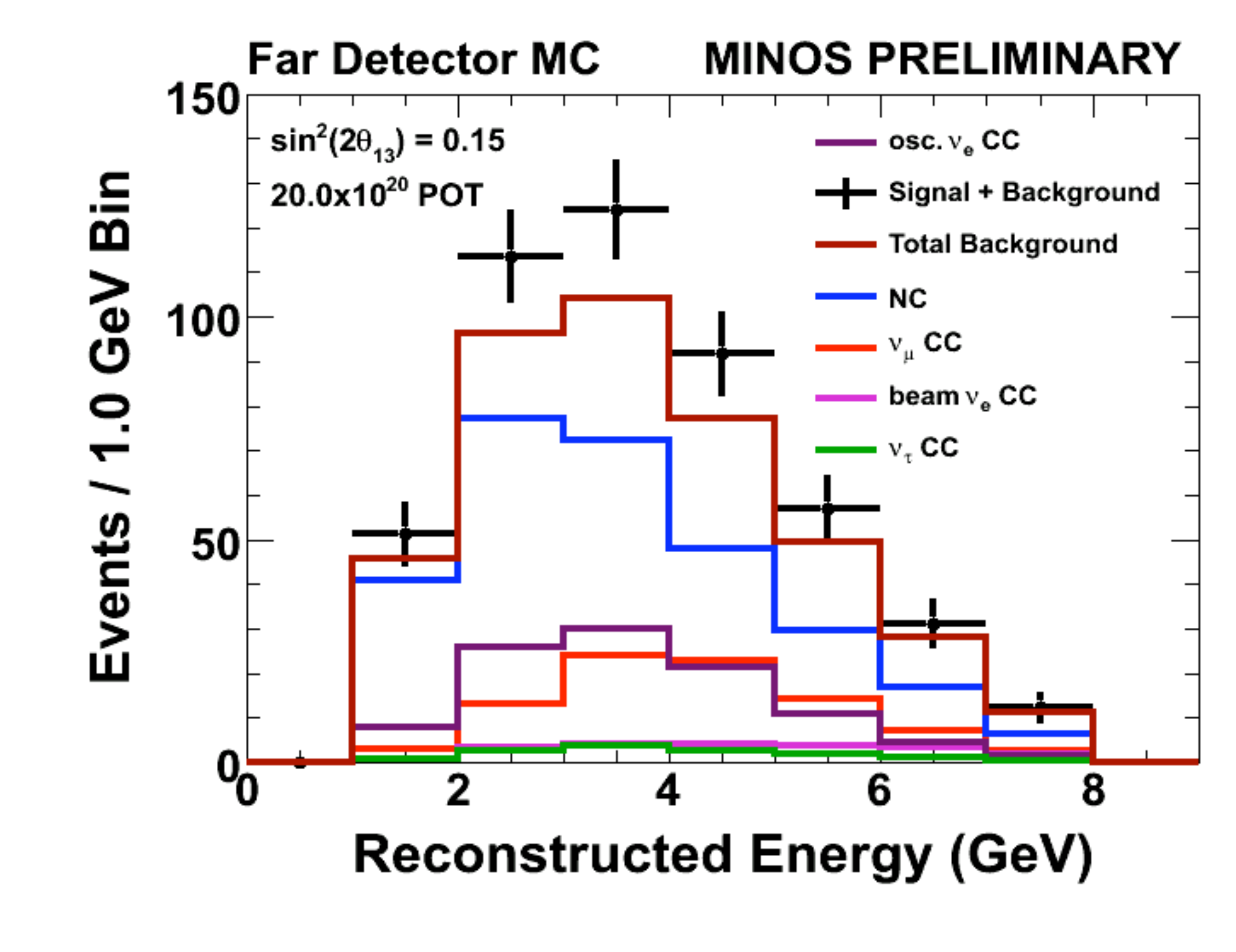
Other Finalized Analyses

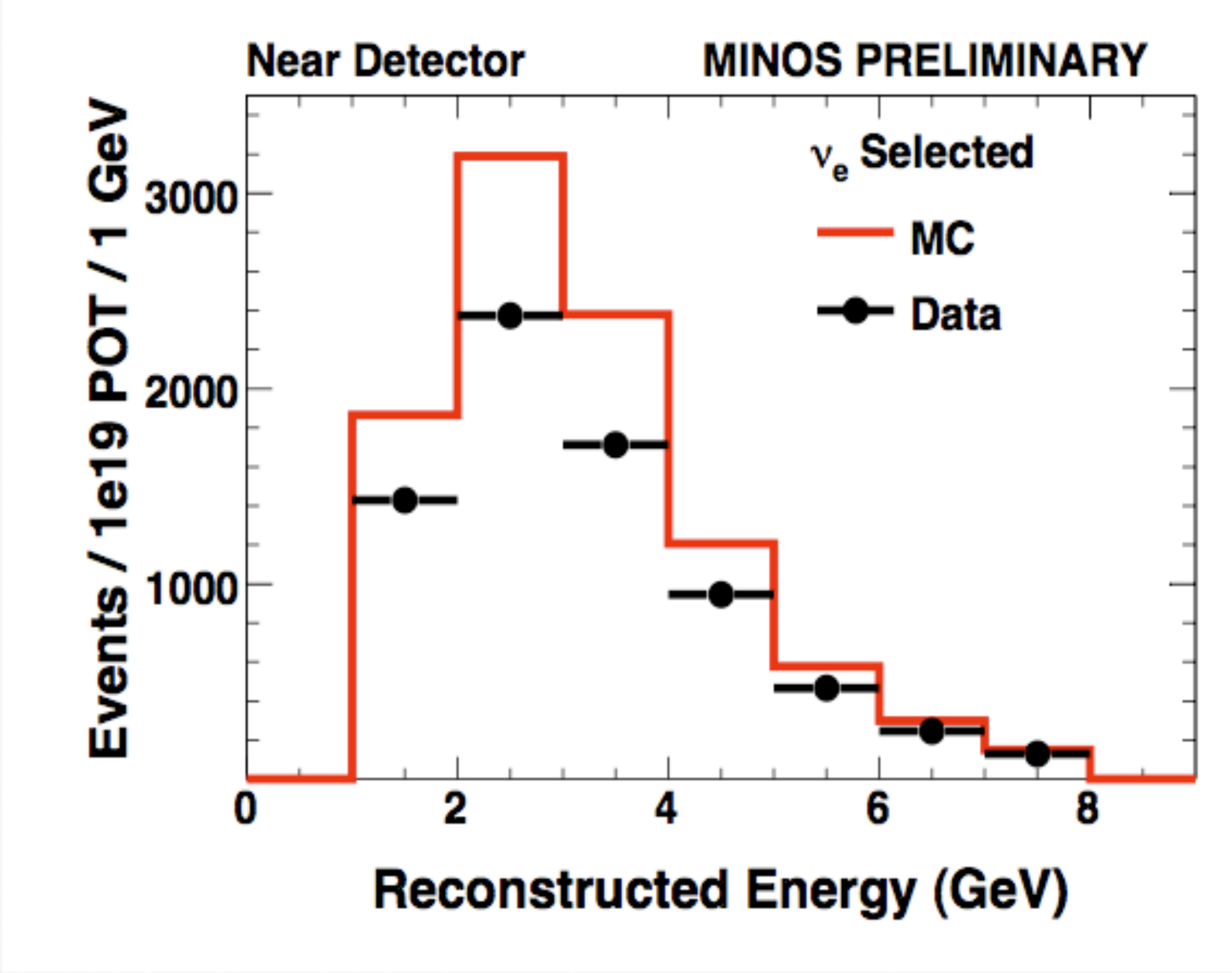
- **"Sudden stratospheric warmings seen in MINOS deep underground muon data"**: High-energy cosmic muon rate is strongly correlated to temperature changes in the upper atmosphere. MINOS has shown that (under)ground-based high statistics cosmic muon measurements are a new tool to be used in tracking meteorological phenomena in the upper atmosphere.
- **"Testing Lorentz Invariance and CPT Conservation with MINOS Near Detector Neutrinos"**: search for a sidereal signal in the MINOS ND. Upper limits set on individual SME Lorentz and CPT violating terms.
- **"Observation of deficit in NuMI neutrino-induced rock and non-fiducial muons in MINOS far detector and measurement of neutrino oscillation parameters"**: see poster by Aaron McGowan

ν_e CC Analysis

The search for ν_e appearance

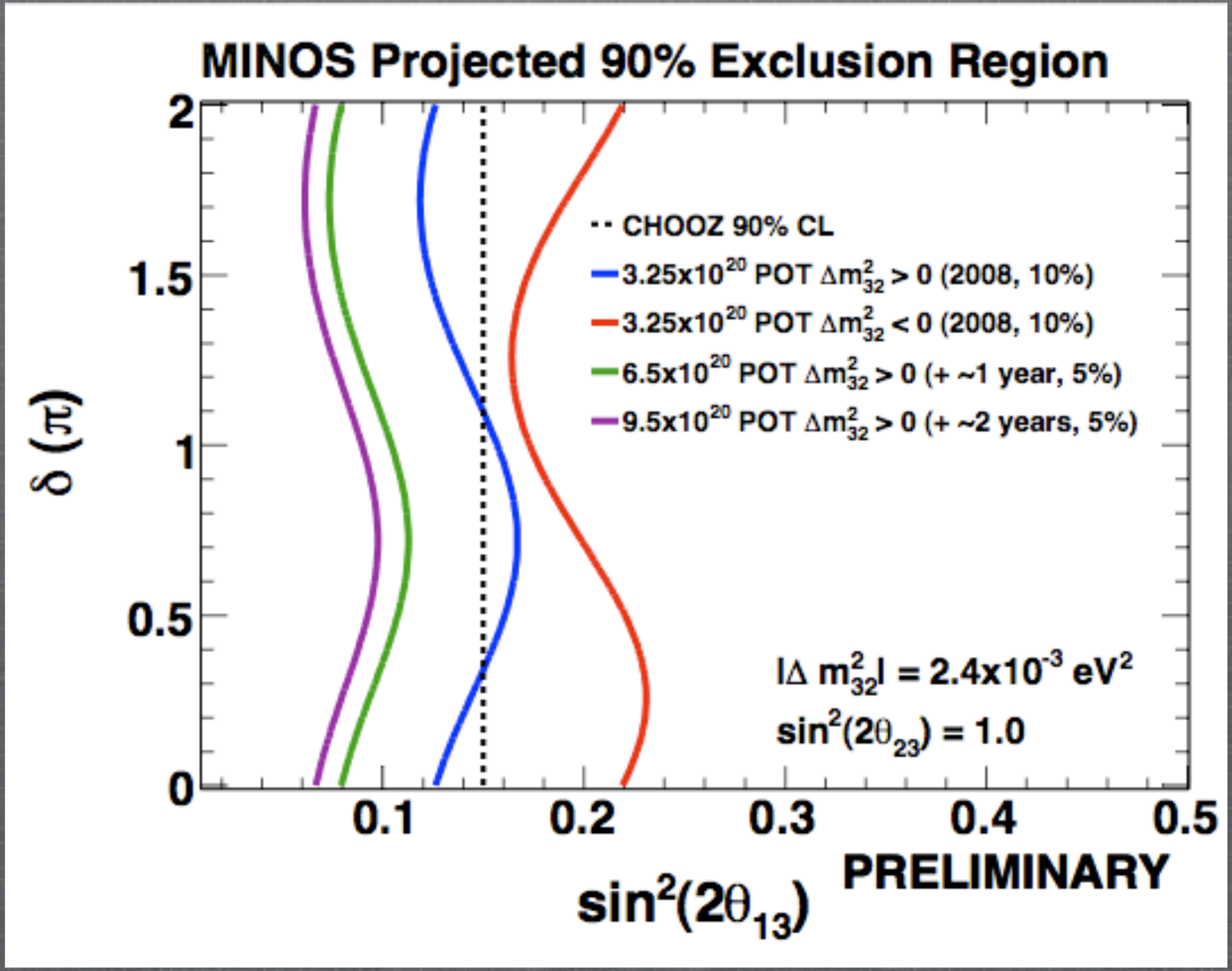
ν_e Background Estimates





- Measurement dominated by backgrounds: at the CHOOZ limit, 12 ν_e events are expected with 42 background events (for 3.25 x 10^{20} POT).
- Dominant backgrounds are NC and ν_μ CC events.
- We see a very large discrepancy between selected ν_e ND MC and data events.
- Two new data-driven methods have been developed to resolve the MC/data difference - see posters by Steven Cavanaugh and Lisa Whitehead for details.

ν_e Sensitivity



- Projected limits for expected MINOS integrated exposures for the next few years.
- MINOS can improve upon the CHOOZ limit by ~x2.

Other Analyses in the Works

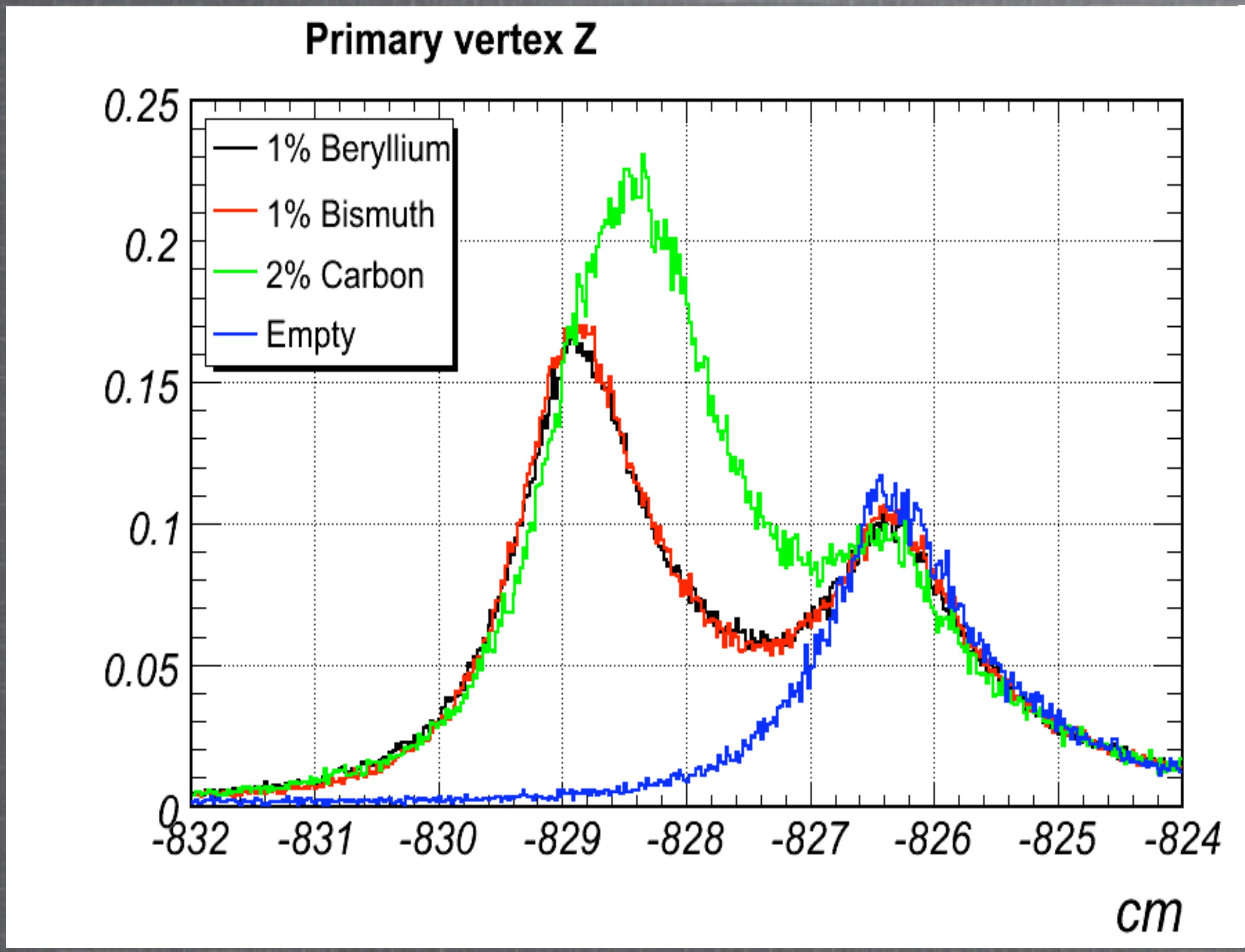
- Anti-neutrino oscillation measurements
- ND measurements:
  - Inclusive CC cross-section and structure functions
  - M_A extraction from quasi-elastic events
  - NC coherent scattering on Fe
  - Cosmic ray studies

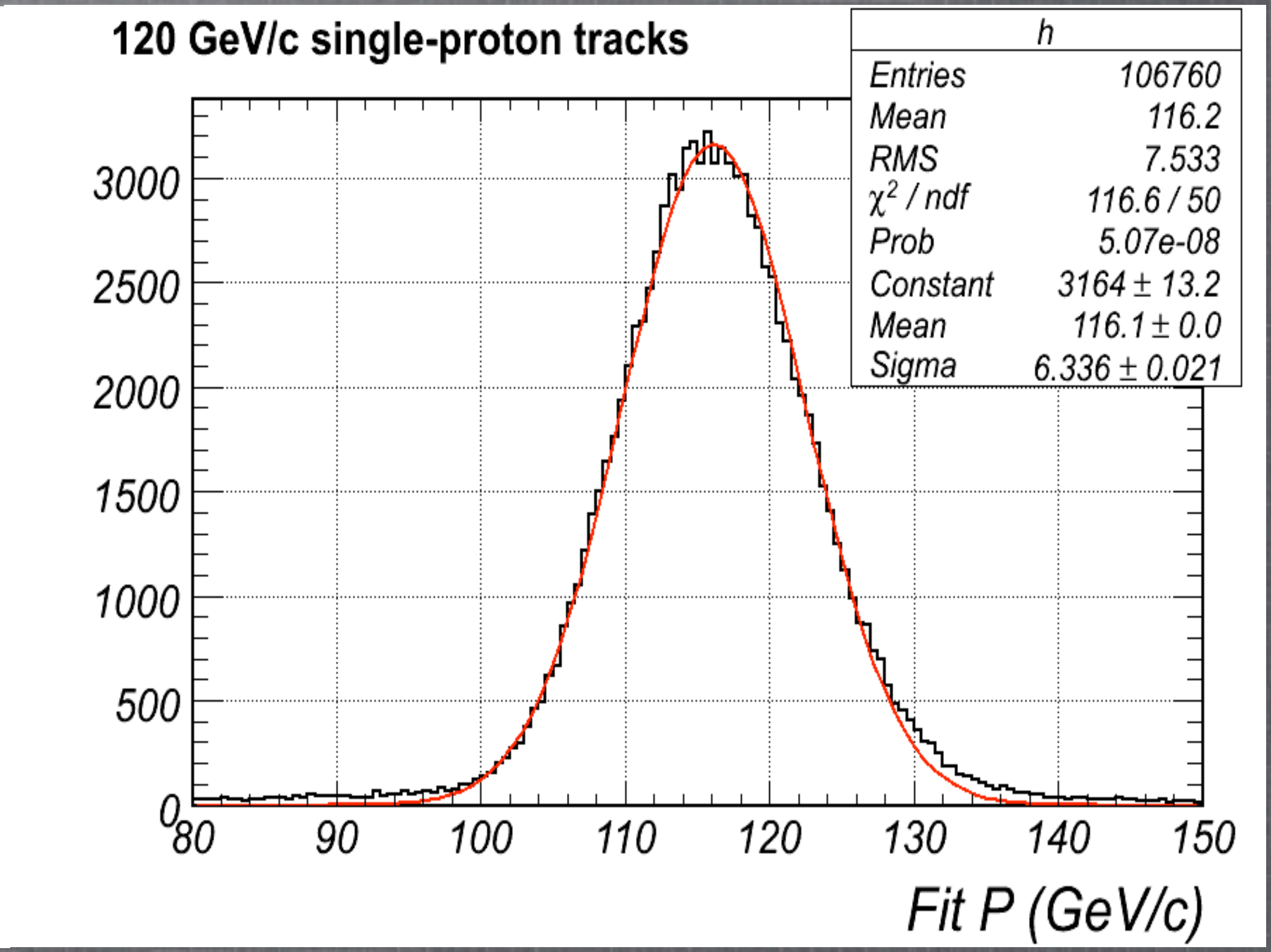
Conclusions

- 2007-08 has been a very productive year for MINOS!
- Latest ν_μ CC analysis results (3.36×10^{20} POT):
  - $\Delta m^2 = (2.43 \pm 0.13) \times 10^{-3}$ eV^2 (68% CL),
  - $\sin^2(2\theta) > 0.90$ (90% CL),
  - Decay and decoherence models disfavored at 3.7 and 5.7 σ respectively.
- NC analysis results (2.46×10^{20} POT): fraction of disappearing NC events < 0.17 at 90% CL.
- Great progress in understanding the backgrounds and systematics in the νe appearance measurement; first results are expected later this year.
- Results from MIPP expected later this year, expected uncertainty on ν flux is ~15%.
- Great progress in ND measurements, results expected soon.
- **Thanks to FNAL AD, CD, and administration for all their hard work and support!**

Backup Slides

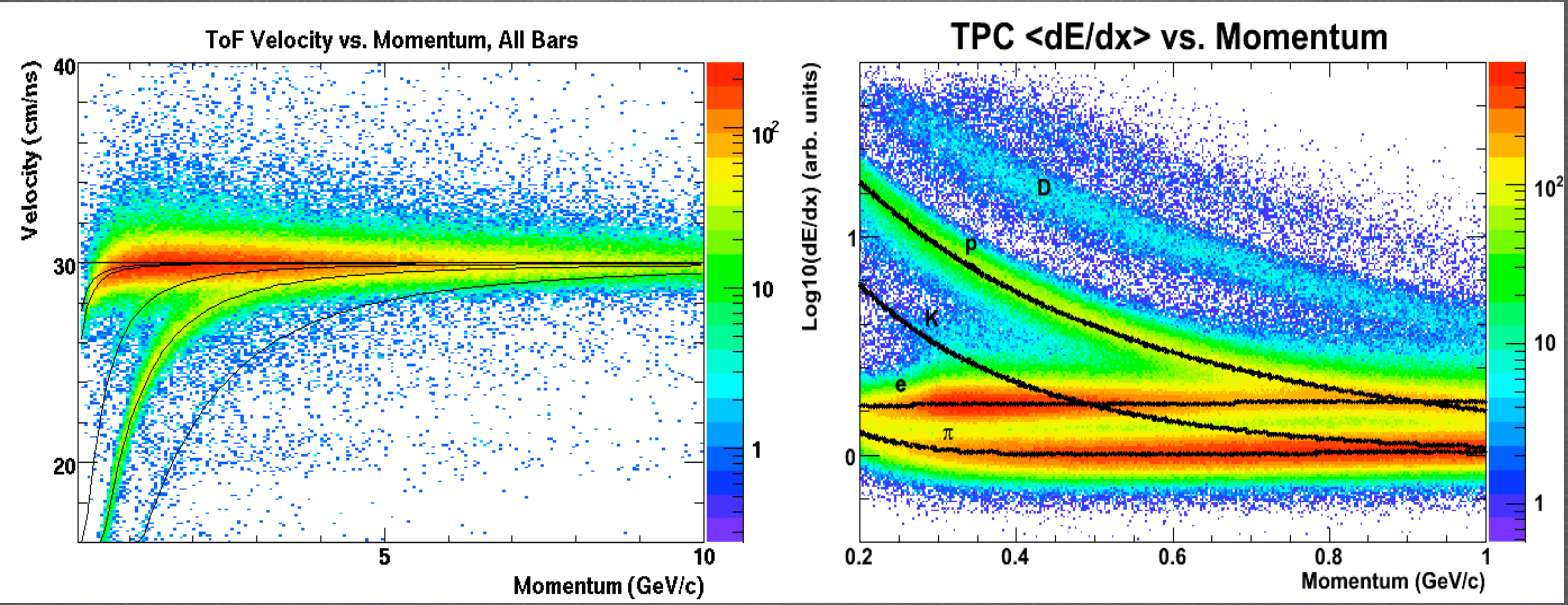
MIPP Performance





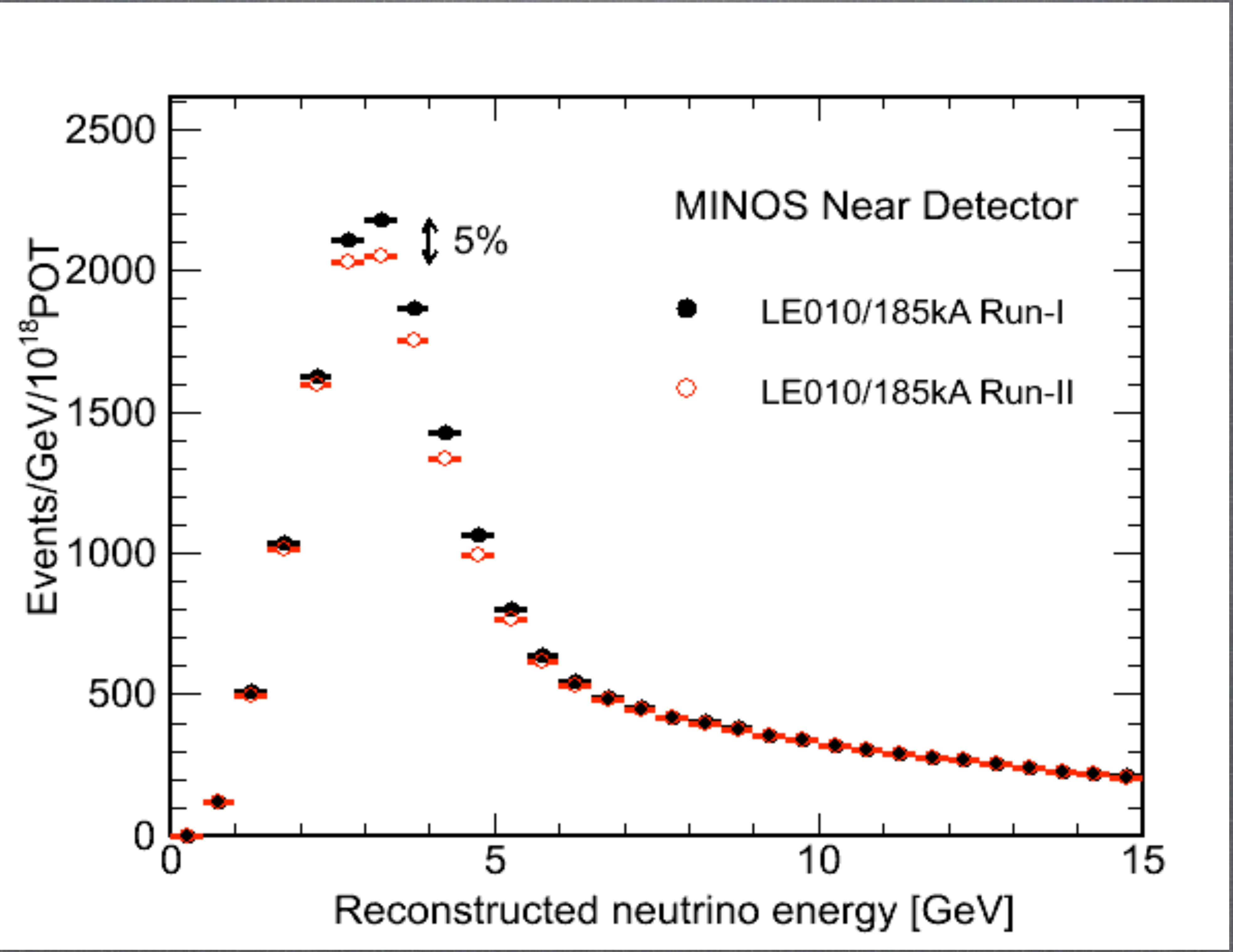
- Momentum resolution is ~5% at 120 GeV/c, much better at lower momenta.
- Vertex resolution is ~8 mm in the beam direction, ~2 mm transverse.
- Reconstructed momentum appears to be systematically low by ~2%.

MIPP Performance



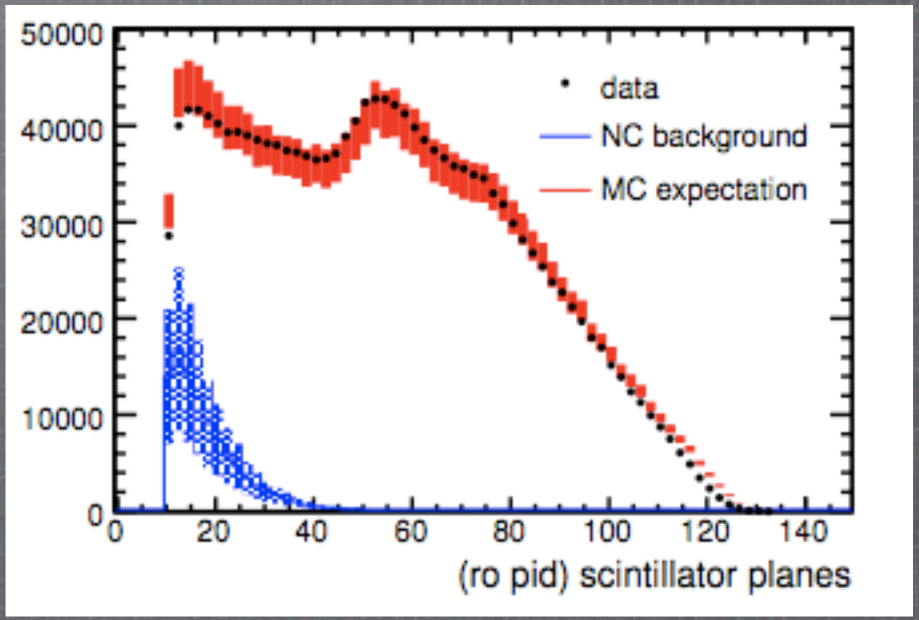
- Ckov has ~5 pe per β=1 particle.
- ToF resolution is ~300 ps
- TPC <dE/dx> resolution is ~12 %.

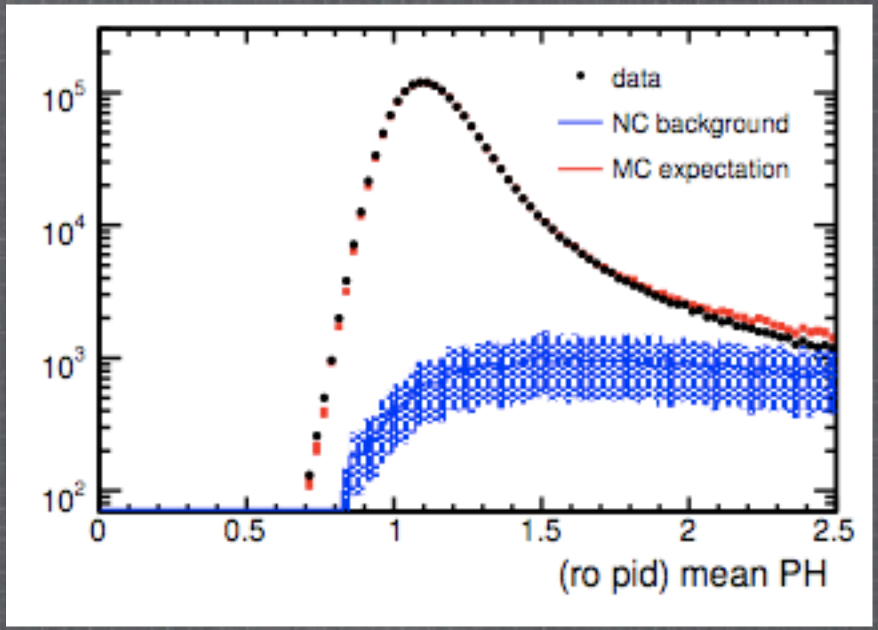
LE1 vs. LE2 Beam Configurations

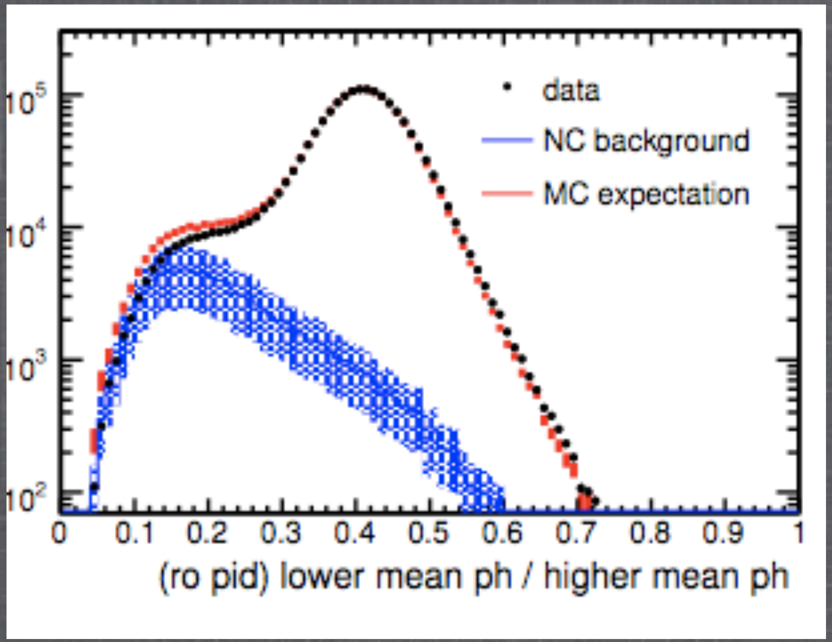


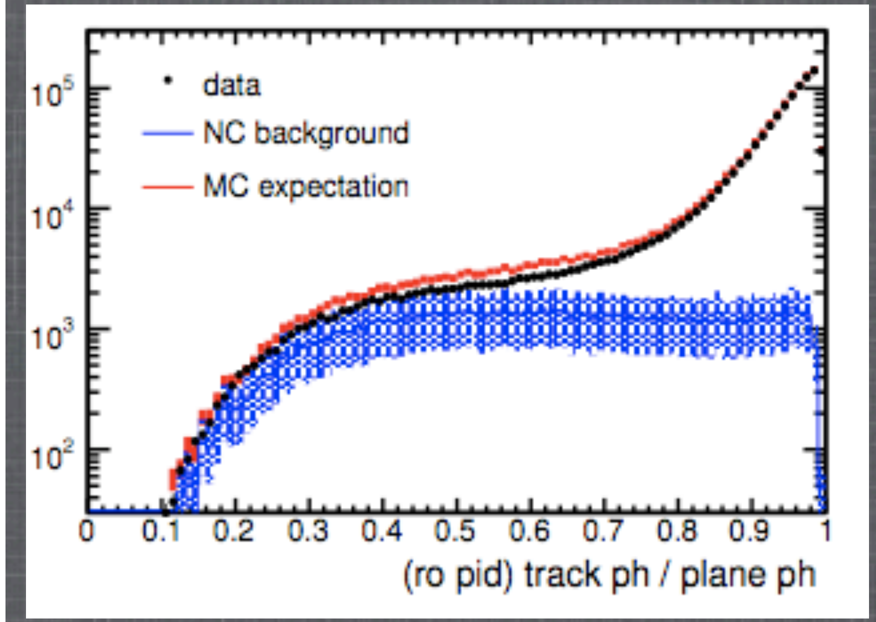
ν_μ CC/NC Separation

- CC/NC separation achieved via a kNN event selection based on:
  - Track length
  - Mean pulse height
  - Fluctuation in pulse height
  - Transverse track profile

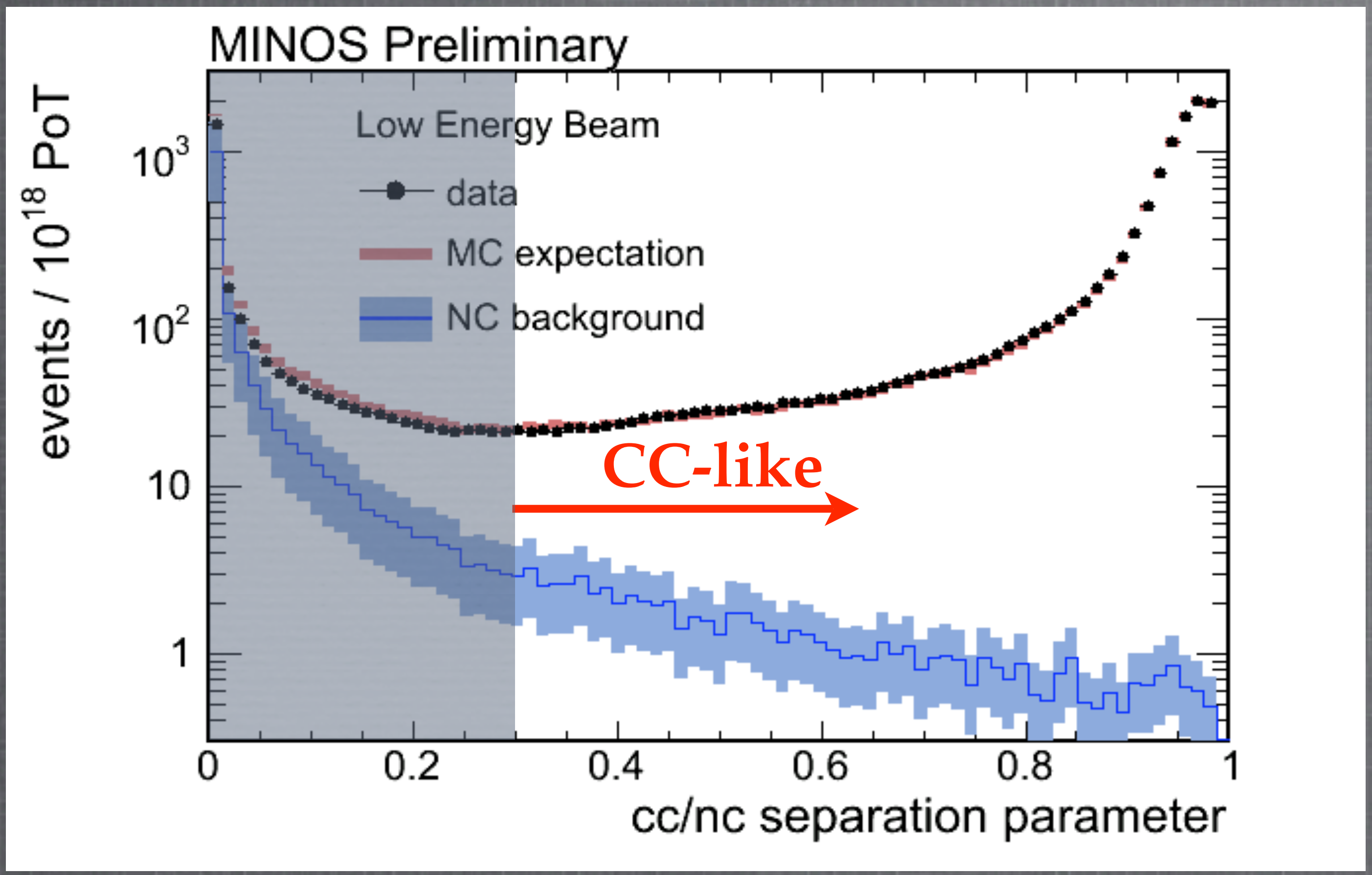


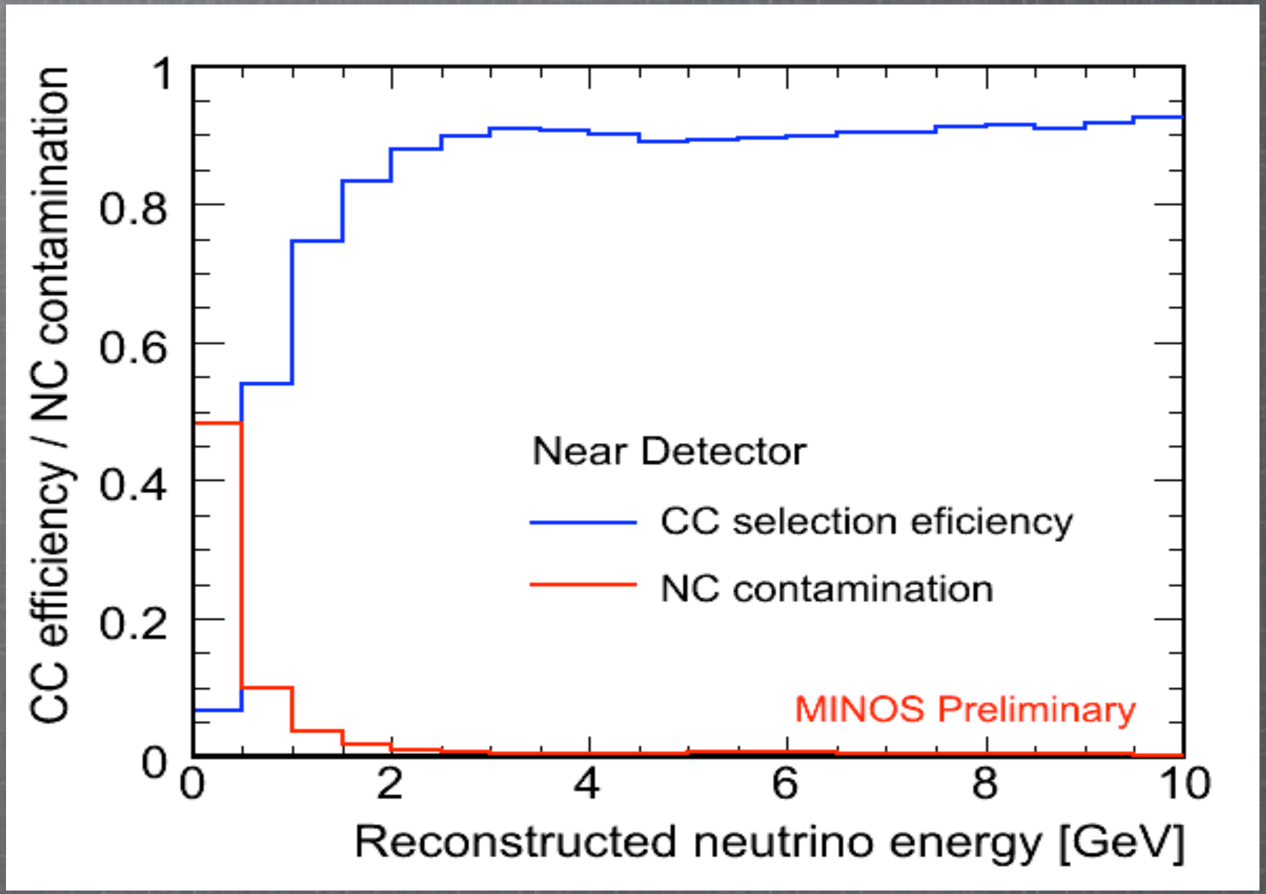






ν_μ CC Event Selection

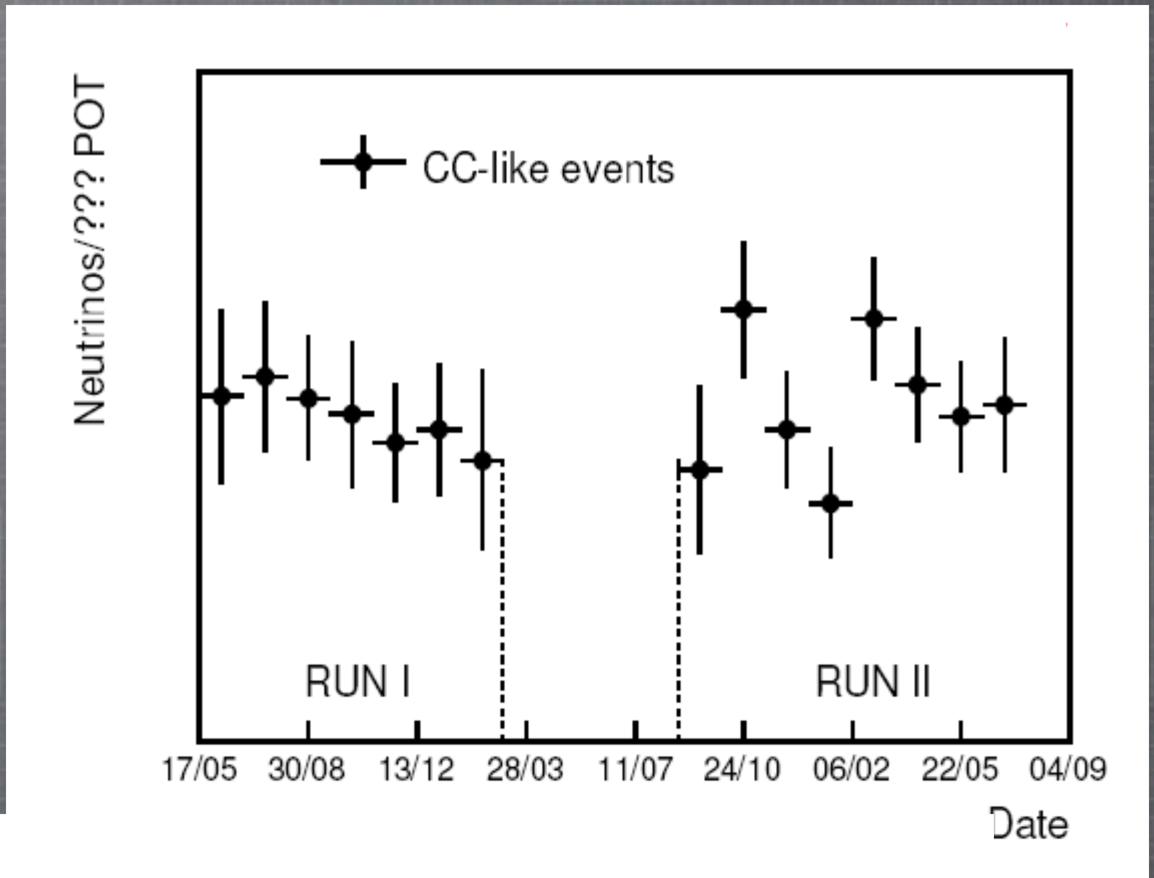


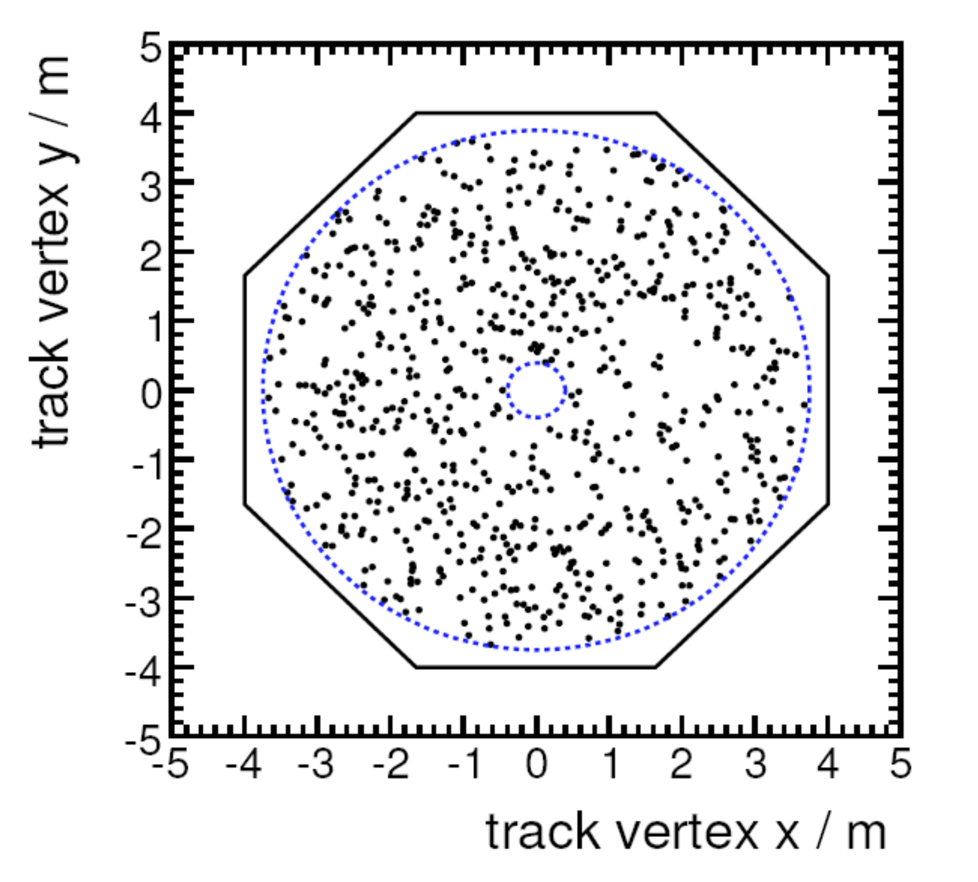


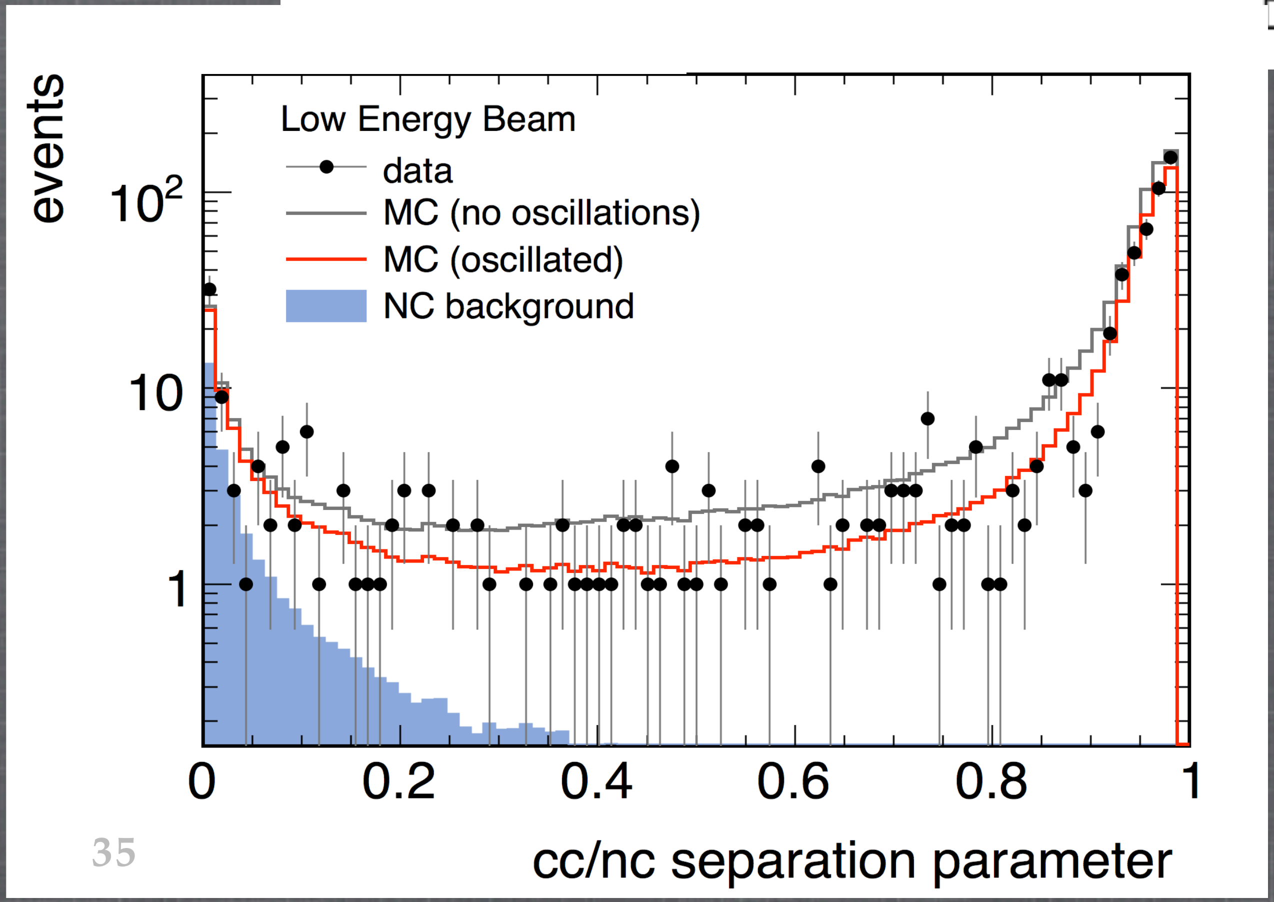
- **Cut on separation parameter maximizes CC selection efficiency and minimizes NC background.**
- **Good agreement between data and MC above the CC/NC separation parameter cut.**

Far Detector Low-level Data Quality Checks

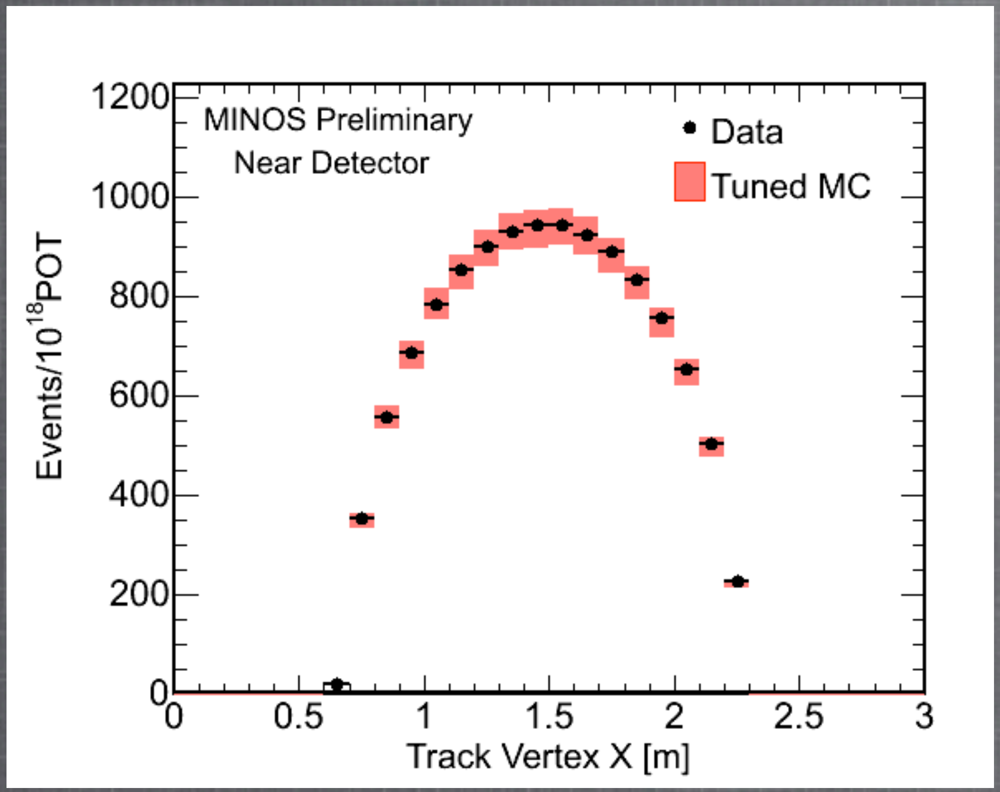
- FD energy spectrum is only looked at after performing:
  - low-level data quality checks
  - procedural checks

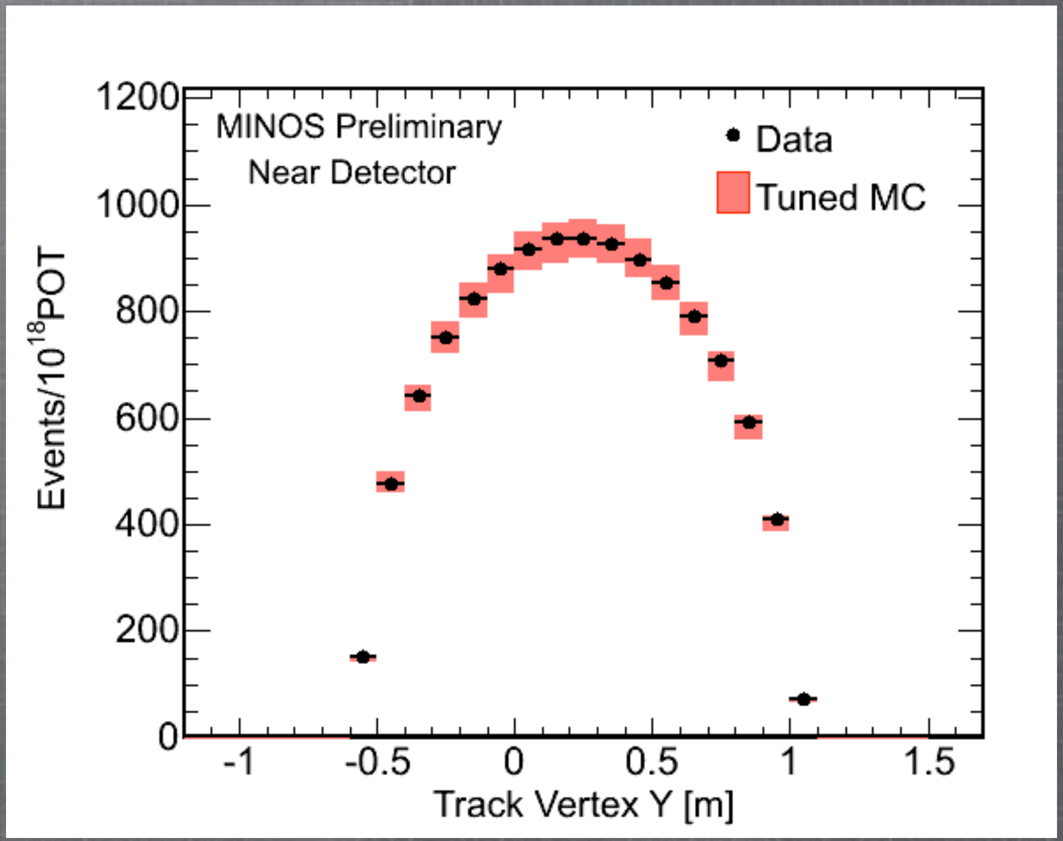


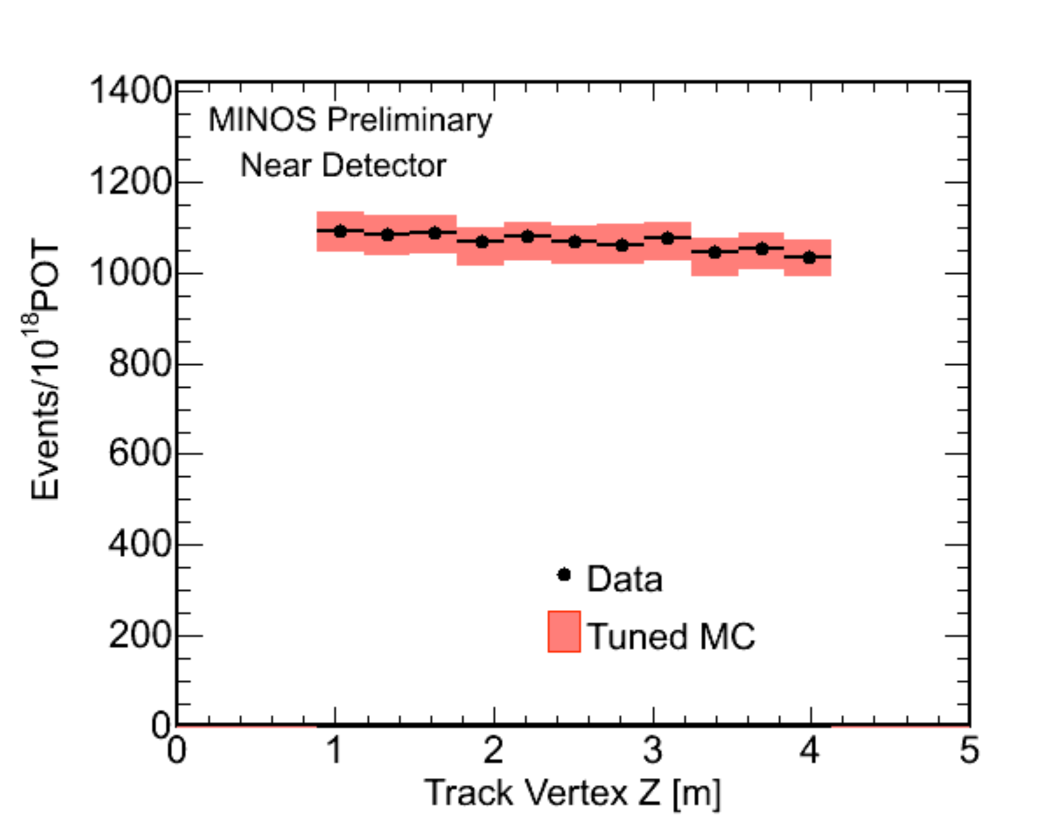




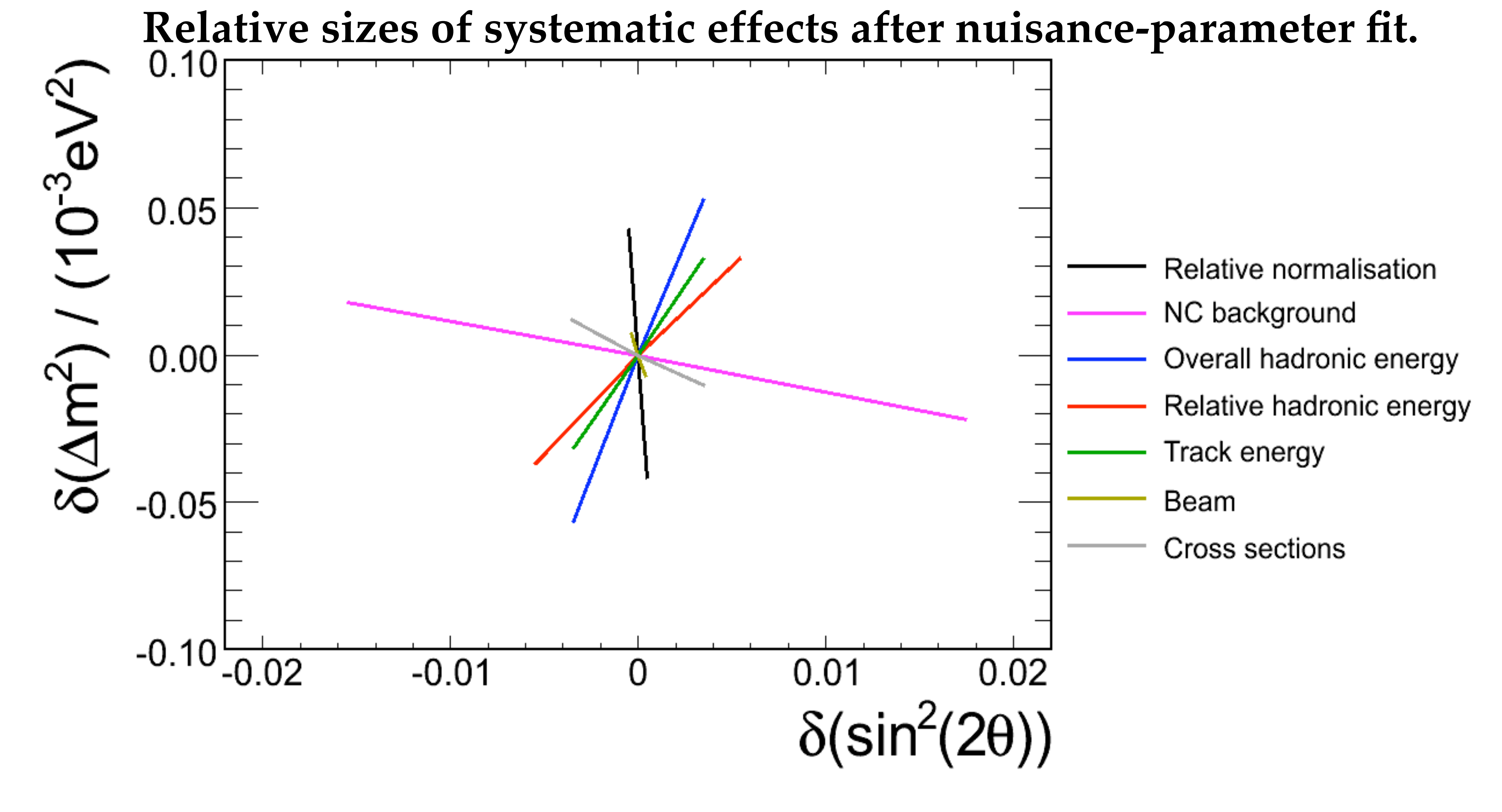
ND Distributions After Making PID Cut







Systematics After the Fit



- Normalization: +1.6%
- NC background: -7%
- Eshower: -4%

Systematics After the Fit

Old/New:
Reco changes: B-field, track finding
MC: hadronization and intranuclear rescattering models
Analysis: Fiducial volume +3% FD, E>30 GeV now kept, new cc/nc seperator. (ROID improves efficiency from 75 to 81% and decreases background from 1.8 to 0.6%).

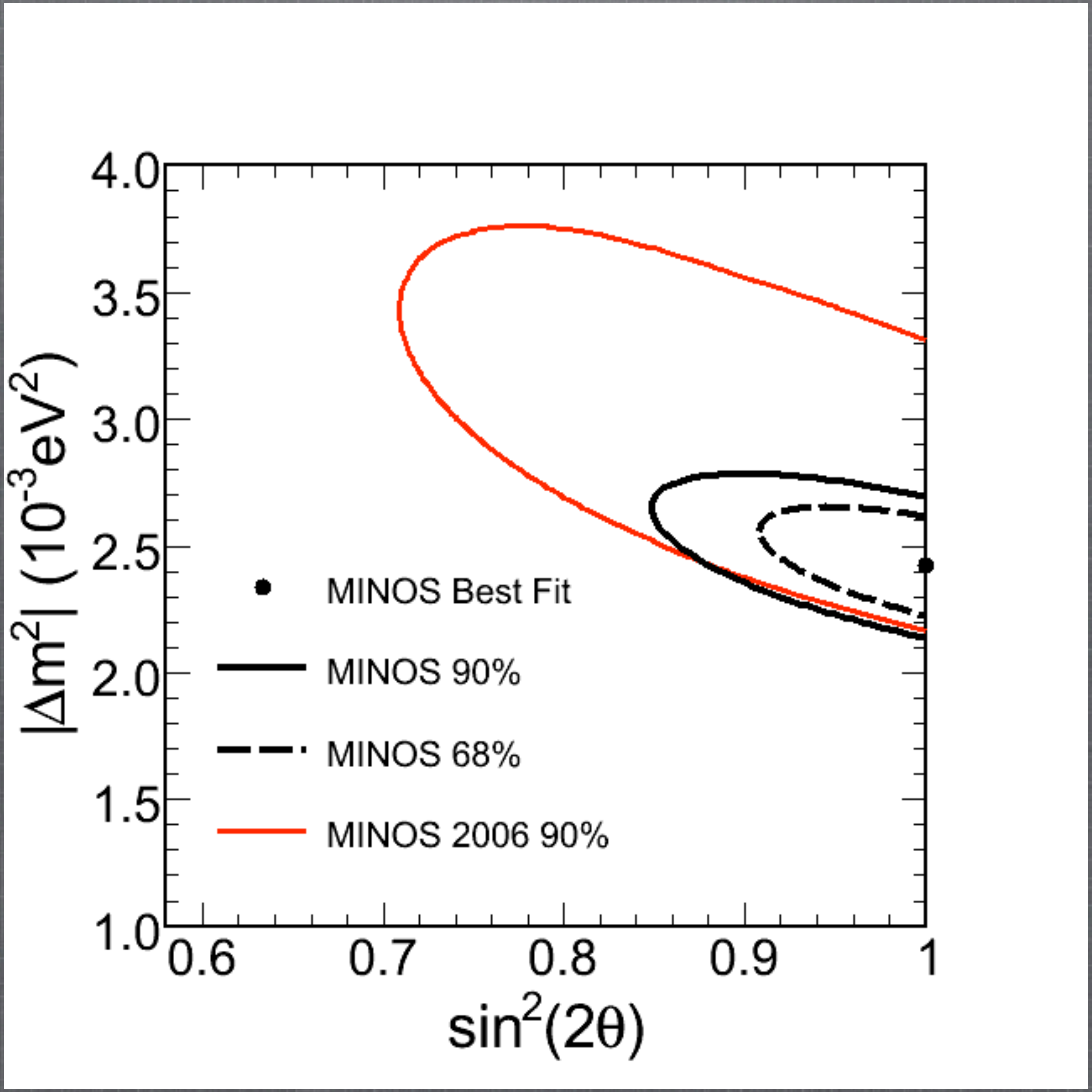
Backgrounds in the FD sample:
NC: 5.9 events, tau=1.5 events, rock mu=2.3 events, CR = 0.7 events

Analysis:	POT(10**20)	# CC	DM2 (best fit 10**-3)
2006	1.27	215	2.74
2007	2.50	563	2.38
2008	3.36	848	2.43

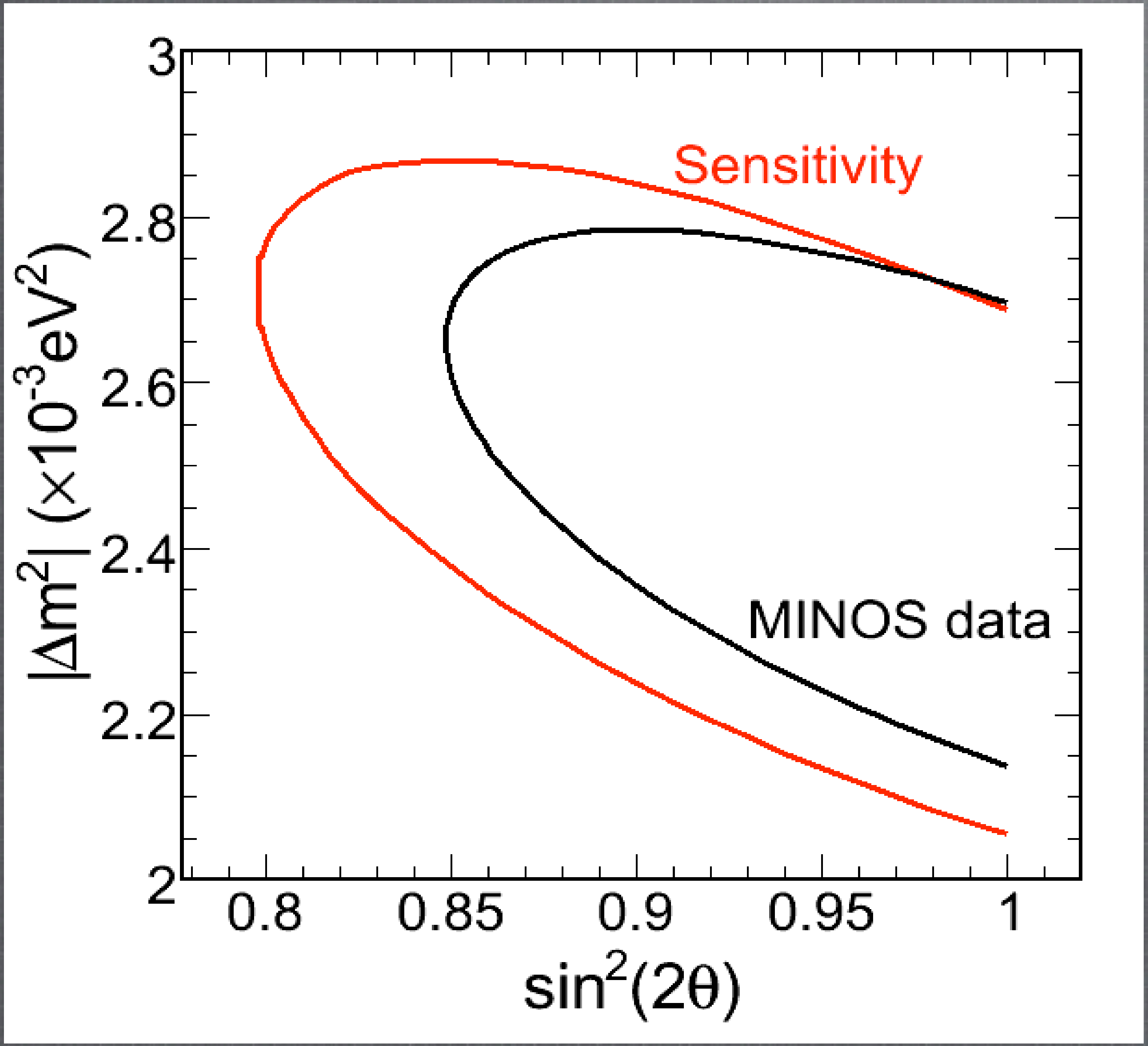
		Best fit		Shift from nominal best fit	
Systematic	Shift	Δm^2_{atm} $/10^{-3}\text{eV}^2$	$\sin^2(2\theta_{23})$	Δm^2_{atm} $/10^{-3}\text{eV}^2$	$\sin^2(2\theta_{23})$
Nominal	—	2.385	1.000	—	—
Far detector normalisation	-4%	2.465	1.000	+0.080	0.000
	$+4\%$	2.305	1.000	−0.080	0.000
NC background	-50%	2.390	1.000	+0.005	0.000
	$+50\%$	2.385	0.996	0.000	−0.004
Overall shower energy scale	-10%	2.315	1.000	−0.070	0.000
	$+10\%$	2.450	1.000	+0.065	0.000
Relative shower energy scale	-2.2%	2.395	1.000	+0.010	0.000
	$+2.2\%$	2.375	1.000	−0.010	0.000
Track energy from range	-2%	2.355	1.000	−0.030	0.000
	$+2\%$	2.415	1.000	+0.030	0.000
FD Track energy from curvature	-4%	2.370	1.000	−0.015	0.000
	$+4\%$	2.400	1.000	+0.015	0.000
SKZP beam errors	-1σ	2.375	1.000	−0.010	0.000
	$+1\sigma$	2.390	1.000	+0.005	0.000
Total ν_μ CC cross section	-3.5%	2.385	1.000	0.000	0.000
	$+3.5\%$	2.385	1.000	0.000	0.000

Table 4: The best fits to sets of systematically shifted data (the fit constrained to $\sin^2(2\theta_{23}) \leq 1.0$), and the shifts of the best fit parameters from the unshifted case.

2006-2008 Comparison



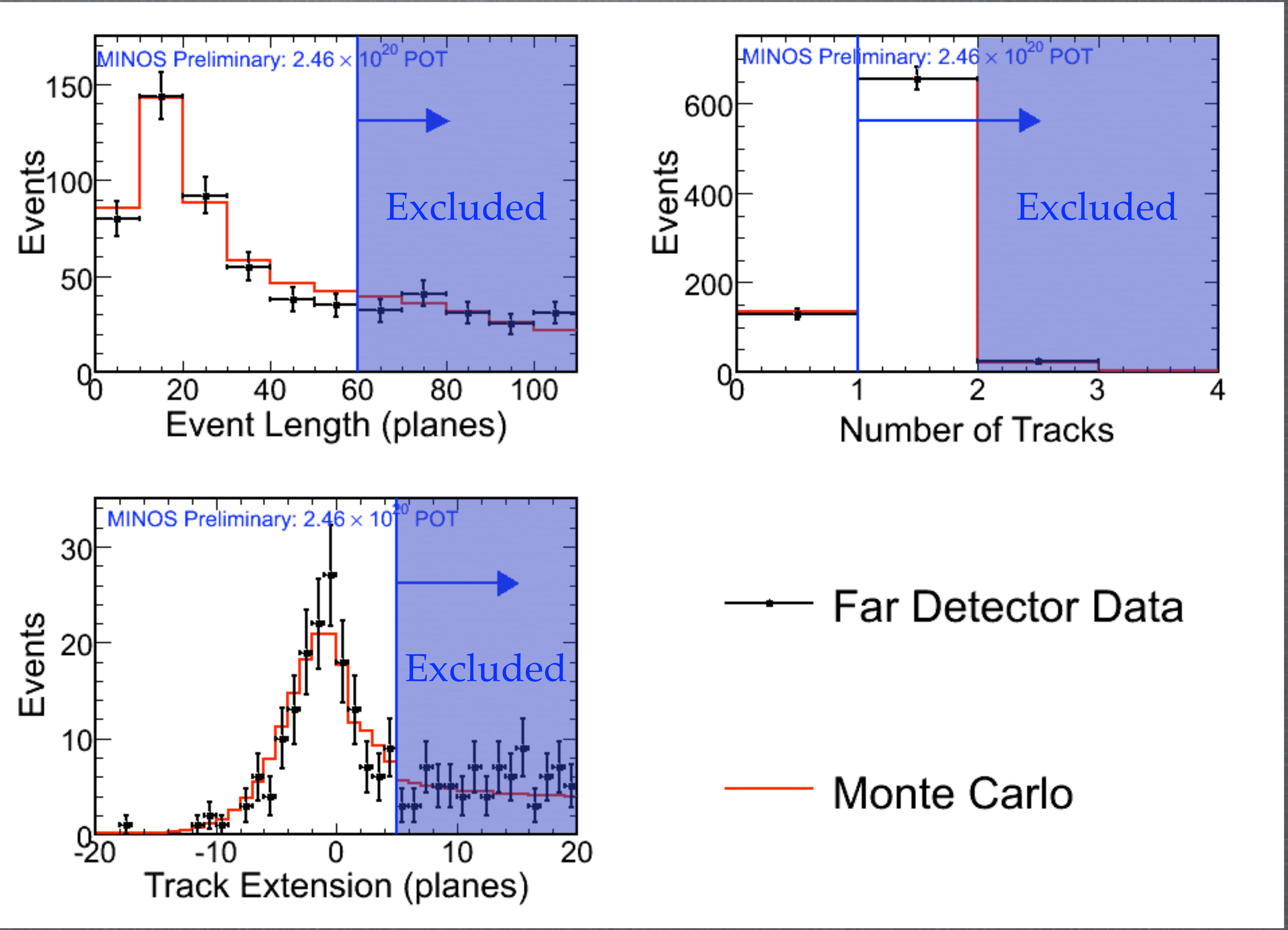
Sensitivity



- Final contour is a bit smaller than the predicted sensitivity because $\sin^2(2\theta)$ falls in the unphysical region.
- A study shows that 26.5% of unconstrained fits have a fit value of $\sin^2(2\theta) \geq 1.07$
- Feldman-Cousins study indicates that our contours are slightly conservative.

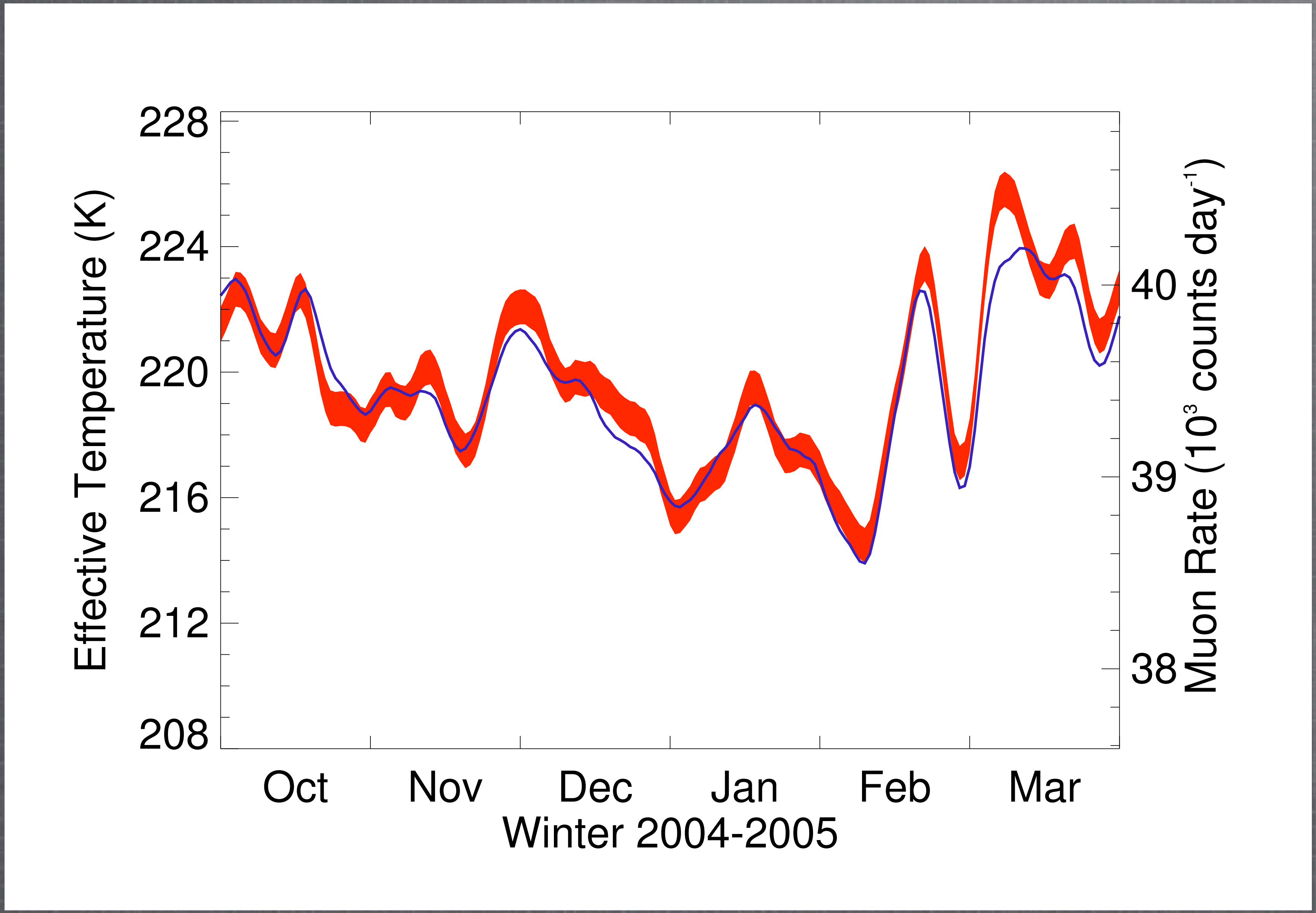
NC Event Selection in the FD

- Identical cuts are made in FD as in ND.
- MC oscillated with 2007 MINOS CC best fit values of $\Delta m^2 = 2.38 \times 10^{-3}\ eV^2$ and $\sin^2(2\theta) = 1$.



Cosmic Rays and Upper Atmospheric Weather

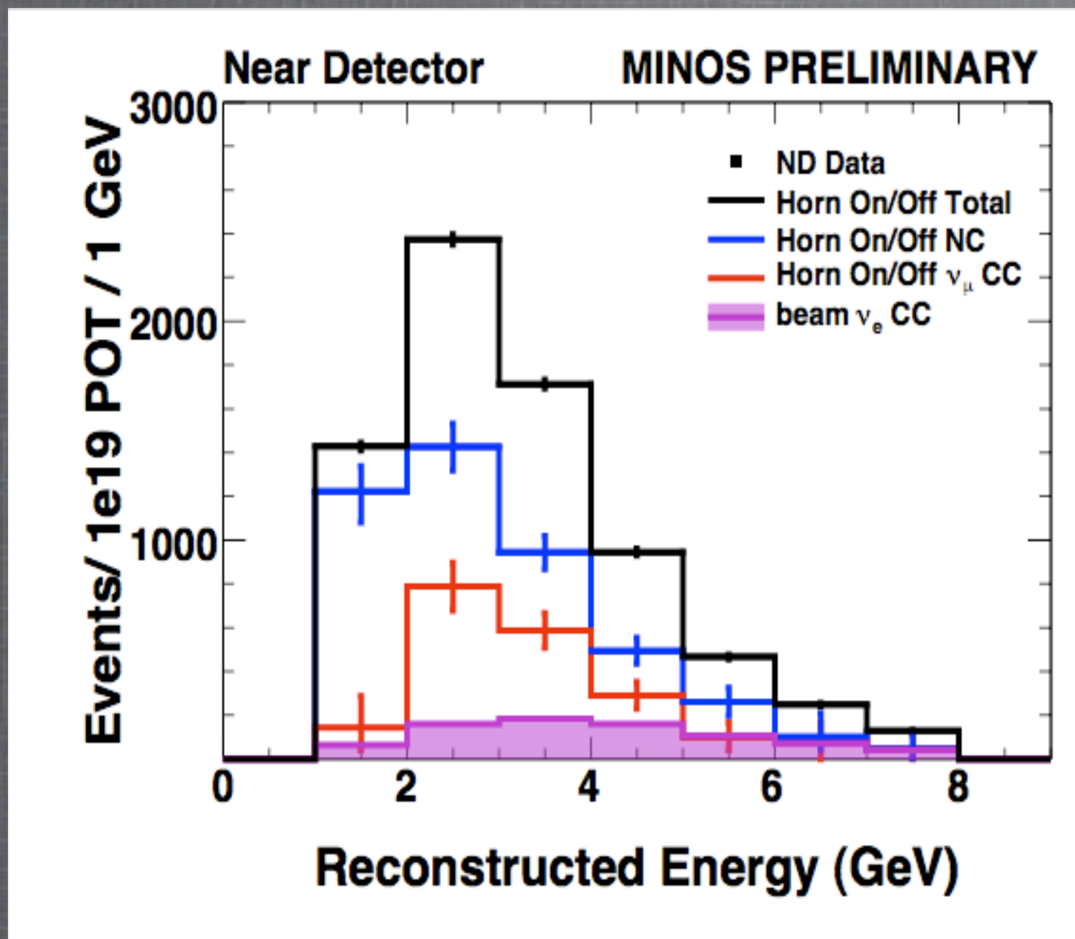
Sudden Stratospheric Warmings

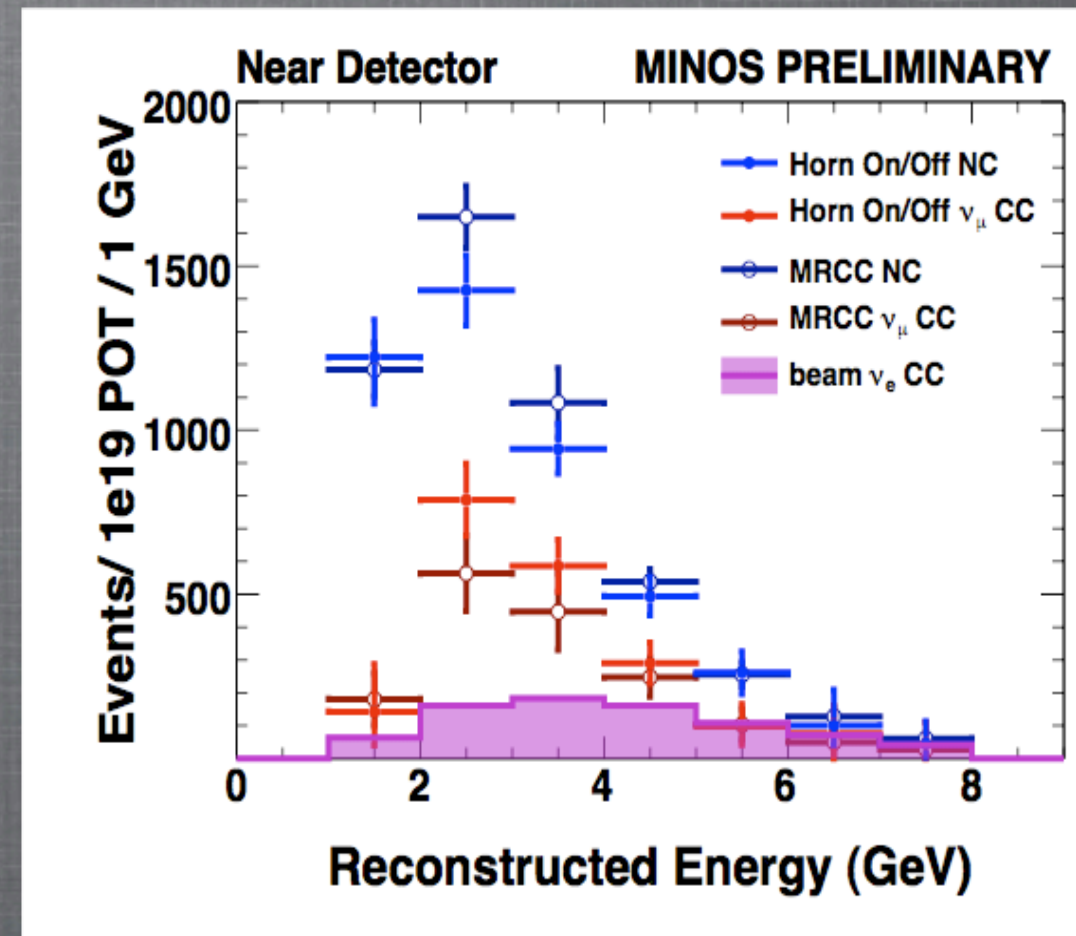


- There is a strong correlation between the high energy cosmic ray rate and temperature changes in the upper atmosphere.
- The MINOS FD observers a large cosmic muons rate and can measure these percent-level changes in rate.

- SSWs have been tracked using balloon measurements, rocket soundings, LIDAR, airborn and satellite observations. MINOS now provides another new tool with which to observe these meteorological phenomena.

ν_e Data-Driven Background Studies





Estimate	Signal ν_e	Total BG	NC	ν_μ CC	Beam ν_e	ν_τ CC
Horn On/Off	12	42	29	8	3	2
MRCC	12	43	32	6	3	2

$\sin^2(2\theta_{23}) = 1.0$
$\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV^2
$\sin^2(2\theta_{13}) = 0.15$
no matter effects
3.25×10^{20} POT

- Horn On/Off - constrain the relative ratios of NC and ν_μ CC background events in two different beam configurations.
- Muon removed hadron showers from ν_μ CC (MRCC).